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Potential Individual Doses from Disposal of High-Level Radioactive Wastes In Geologic Repositories

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The Agency has recently published environmetnal standards addressing disposal of high level radioactive wastes (40 CFR Part 191) for public review and comment (47 FR 58196). An important part of this effort is the evaluation of how effective mined geologic repositories are for isolating these wastes from the environment for many thousands of years. EPA's assessments indicate that carefully designed repositories at good sites can keep long-term risks below those that would exist if (on a generic basis) the uranium ore used to create the wastes had not been mined initially. Accordingly, the Agency has proposed environmental standards that would restrict projected releases from high-level waste disposal systems--for 10,000 years after disposal to levels that should keep the risks to future generations less than those to which they would have been exposed from the unmined ore if these wastes had not been created.
This technical report presents the methodology used to assess the potential annual individual doses and human exposure and geologic media contamination probabilities from projected releases of radioisotopes from a geologic repository. It describes the models that the Agency employed for this analysis and reviews the various assumptions which were made. Since this analysis is necessarily generic in nature, the methodology uses very general models of environmental pathways and considers a range of values for the various parameters used in the models.

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FOREWORD

The Agency has recently published environmental standards addressing disposal of high-level radioactive wastes (40 CFR Part 191) for public review and comment (47 FR 58196). An important part of this effort is the evaluation of how effective mined geologic repositories are for isolating these wastes from the environment for many thousands of years. EPA's assessments indicate that carefully designed repositories at good sites can keep long-term risks below those that would exist if (on a generic basis) the uranium ore used to create the wastes had not been mined initially. Accordingly, the Agency has proposed environmental standards that would restrict projected releases from high-level waste disposal systems--for 10,000 years after disposal --to levels that should keep the risks to future generations less than those to which they would have been exposed from the unmined ore if these wastes had not been created.

This technical report presents the methodology used to assess the potential annual individual doses and human exposure and geologic media contamination probabilities from projected releases of radioisotopes from a geologic repository. It describes the models that the Agency employed for this analysis and reviews the various assumptions which were made. Since this analysis is necessarily generic in nature, the methodology uses very general models of environmental pathways and considers a range of values for the various parameters used in the models.

Because much of this methodology is new, the Agency is publishing this report in draft form. During the public comment period regarding 40 CFR 191, a Subcommittee of the Agency's Science Advisory Board will conduct an independent technical review of our risk assessments (48 FR 509). All meetings of this Subcommittee will be announced in the Federal Register and will be open to the public.

In addition, I encourage users of this report to submit any comments or suggestions they might have. Such comments would be most helpful if received by May 2, 1983. They should be sent to: Central Docket Section (A-130); Attn: Docket No. R-82-3; Environmental Protection Agency; Washington, D.C. 20460.

Richard J. Guimond

for Glen L. Sjoblom
Director
Office of Radiation Programs

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Chapter 1

Summary

1.1 Introduction

This report presents potential annual dose equivalents (hereafter called doses or dose rates) to individuals exposed to radionuclides released from a high-level waste repository to groundwater (aquifers) or to the earth's surface. The modeled repository is filled with spent reactor fuel elements that have been packaged in canisters. The repository is deep below the earth's surface. Four shafts needed in building and filling the repository have been resealed. In this report, we consider repositories placed in bedded salt and granite, and provide separate results for releases from repositories in each host medium. The salt repository has an overlying and an underlying aquifer; the granite repository has only an overlying aquifer. Nuclides can be released from the repositories to man's environment as a result of direct removal of the waste to the surface, direct contact between the waste and groundwater and subsequent transport to an aquifer, or release of water from a region of contaminated porous backfill to the surface. The backfill water becomes contaminated after failure of the canisters by corrosion. The region of contaminated backfill in a granite repository is called the "granite tank"; contaminated water in a salt repository is contained in "brine pockets."

1.2 Nuclide Releases

We examined seven ways in which nuclides can be released from a deep mined geologic repository into the bioshpere. The first four types of release are caused by someone drilling into the repository in search of resources: 1) the drill hits radioactive waste and brings it to the land surface; 2) the drill hits waste and releases radionuclides to the aquifer; 3) the drill does not hit waste directly, but enters a brine pocket or granite tank, releasing radionuclides to the land surface; 4) the drill intersects the tank or brine pocket, releasing radionuclides to the aquifer.

Events five and six involve fault movement in the area of the repository: 5) the fault directly hits waste in a row of canisters, releasing nuclides to the aquifer; 6) the fault disrupts the tank or brine pocket, and radionuclides are released to the aquifer. And finally, 7) radionuclides are released from the repository to the aquifer because of shaft seal leakage.

We selected drilling for consideration because it would release more waste than leakage through a resealed borehole would, and because it would produce a more concentrated release than flow through bulk rock. We selected faulting because it would release more waste than a breccia pipe would. We omitted releases from volcanic action, igneous intrusions, and meteorite impacts, as too improbable to serve as a basis for regulation.

1.3 Nuclide Transport

For a release to the land surface, we calculated annual dose rates to the lungs from inhaling contaminated air near the drilling site. Our model assumes that when a person drills into the repository and hits the waste, 15% percent of the waste from one canister, in its original insoluble form, will be carried to the surface by the drill bit. Once the waste is deposited on the land surface, a portion of the nuclides will disperse into the air. We assume average dispersion conditions, and we assume the wastes disperse radially from the point source. The nuclides will eventually be removed from the land surface by radioactive decay and infiltration into the soil.

Nuclides released to the land surface by drilling into contaminated repository water are in a soluble chemical form. The amount of material released is different from that released by a direct hit on waste. For example, the granite tank inventory of americium (Am)-241, the most harmful nuclide in the inhalation pathway, increases for about 1200 years. However, as nuclides leach out of the waste matrix and into the tank, they are decaying. Eventually, the inventory in the tank declines because of radioactive decay. Drilling into granite removes 200 cubic meters (m^3), or 0.01%, of the contaminated water. The nuclide content of this water is smaller than that which would be released by a direct hit on waste, and consequently doses are smaller. Drilling into a brine pocket (0.06 m^3) releases an even smaller quantity of contaminated water and the doses are very small.

We calculated the effects of both the leach rates of the waste matrix and the solubilities of the nuclides as they affect the entrance of the nuclides into the aquifer. Leach rate refers to the rate at which the waste matrix in contact with groundwater degrades and allows nuclides to filter into the groundwater. For many nuclides, the leach rate is the limiting factor controlling their rate of entry into the aquifer (leach-limited nuclides). For some other nuclides, the rate of entry into the aquifer is further limited by their low solubility in groundwater (solubility-limited nuclides).

We studied three drilling releases to aquifers: a direct hit into the waste, penetration into a brine pocket, and penetration into a granite tank. We assume the drill produces a borehole down through the repository and into any lower aquifer, and that nuclides can flow through the borehole into the upper aquifer. Transport within the aquifer is the same in all three cases, but the rates at which the nuclides enter the aquifer differ in each case. For a direct hit on waste, the rate of entry into the aquifer of those nuclides that are leach-limited is the product of the leach rate and the nuclide inventory in the affected waste. This inventory is reduced by radioactive decay beginning when the repository is sealed and also by depletion by leaching removal beginning at the time of drilling. The rate of entry of solubility-limited nuclides is equal to the water flow rate through the repository times the solubility. The rate of entry of nuclides into the aquifer from a brine pocket or granite tank initially increases as the nuclides leave the waste matrix and enter the tank or pocket. Eventually, however, the rate of entry into the aquifer decreases as the nuclides in the tank or pocket decay.

Two faulting scenarios assuming nuclide transport to an overlying aquifer were developed. One assumed that the waste was still lined up in its canisters while the other assumed that nuclides had leached into the repository water. After the fault broke open the canisters, we treated the row of waste as a line source, and summed the effect by integrating in the fault line from the upstream boundary of the repository to the downstream boundary. Upstream and downstream refer to the direction of flow in the upper aquifer. Faulting also disturbs the contaminated water in the repository. The concentrations and doses from faulting are the highest found in the study, in part because fault movement affects the largest fraction of the repository. Chapter 4 presents a detailed mathematical discussion of all the releases covered in this report.

1.4 Annual Dose Rates and Contaminated Areas

Chapter 5 presents the results of the dose calculations for the reference repositories. We present here only the annual dose rates from events occurring 1000 years after the repository is sealed. For drilling, we calculated the annual dose rates at selected times (dose times) after the 1000-year event and at pre-selected distances from the borehole.

A drill that hits the solid waste brings 15% of the waste from one canister to the surface. The largest annual dose rate is incurred by breathing contaminated air close to the drilling site (20 meters) ten years after the event. The dose rate is about eleven rem per year (rem/yr) to lungs, mostly from Am-241. At longer times after the drilling, plutonium (Pu)-239 and -240 become dominant, as dose rates fall from about 4 rem/yr at 1000 years after the event to less than 20 millirem per year at 10,000 years. About ten hectares are contaminated enough to give more than 0.5 rem/yr for the first 100 years. As the nuclides decay, these areas drop to zero after 2000 years.

The same direct hit drilling event will also cause nuclides to be released to the aquifer. The largest dose rate from drinking contaminated aquifer water is about 600 rem/yr to the red bone marrow, again from Am-241, at 1000 years after the event and 20 meters from the initial point of release. No areas are contaminated enough to give more than 0.5 rem/yr until 1000 years after the event, when Am-241 has traveled the 20-meter distance and contaminated 0.33 hectares to this extent. Contaminated areas then increase as the nuclides spread, and eventually decrease because of radioactive decay. We did not calculate dose rates from water at distances less than 20 meters because they would not be representative of the water produced by a well at such distances. A well brings in water from a considerable extent of the aquifer, and only a small part of the aquifer would be contaminated close to the borehole because of very limited transverse spread of nuclides.

Drilling releases from the brine pocket are different than releases from the granite tank. The releases to the land surface from a brine pocket feature Am-241 and -243 as the dominant nuclides, but the maximum dose rate, 20 meters away and 10 years after the event, is only 0.02 rem/yr. Land areas contaminated by releases from the granite tank to give more than 0.5 rem/yr are very small, and by 200 years they are zero.

Drilling releases to the aquifer from the granite tank and brine pocket are also modeled differently. The volume of the brine pocket is 0.06 cubic meters (m^3, about 16 gallons), so the concentration of americium isotopes is limited by their solubility. The peak dose rate occurs at 20 meters and 1000 years after the event, and is about 1200 rem/yr, mostly from Am-241. The annual dose rates drop as time passes and nuclides decay. The model calculations do not show any areas contaminated enough to give more than 0.5 rem/yr until the americium isotopes have traveled 20 meters, which takes 1000 years. Then, about 0.35 hectares (1 hectare = 10^4 m^2) are contaminated enough to give more than 0.5 rem/yr; this increases to 6.8 hectares (ha) at 10,000 years. The granite repository dose rates follow the same course. The highest dose rate in granite, also from Am-241 and -243, is about 1800 rem/yr. The areas contaminated are slightly larger, 0.4 ha to give more than 0.5 rem/yr at 1000 years. The contaminated area reaches its maximum of 7.8 ha at 10,000 years.

Fault movement affects either a row of waste canisters, brine pockets, or the granite tank and produces a direct pathway to the aquifer. The faulting event that hits waste directly produces a maximum dose rate of 600 rem/yr, 95% from Am-241. The highest dose rate occurs 500 years after the faulting, and is the same at all locations along the aquifer above the repository. As the Am-241 decays, Am-243 becomes dominant 5000 years after the event. Releases from the granite tank caused by fault movement result in a maximum dose rate of 340,000 rem/yr, 100 years after the event. This is the highest release and annual dose rate in the base case.

Releases from shaft seal leakage occur only in a granite repository. They begin when the canisters fail 500 years after the repository is sealed. The model is the same as for drilling into a granite tank, but the cross-sectional area of the shaft is used instead of that of the borehole, (25.0 square meters (m^2) vs. 0.1 m^2); and the initial permeability is 10,000 times lower. These two factors combine to give somewhat lower flow and lower doses. The maximum dose rate is 1300 rem/yr, 95% from Am-241. About 0.35 hectares are contaminated enough to give more than 0.5 rem/yr, compared to 0.36 hectares for the granite tank drilling case.

1.5 Results of Varying System Characteristics

Chapter 5 presents the results of varying model parameters to determine the sensitivity of our model to input changes. Four of the six modified input parameters affect the rate of release of the nuclides from the repository. They are: 1) the canister life; 2) the borehole permeability; 3) the leach rate of the waste matrix; and 4) the solubility limits of the nuclides.

We examined canister lives of zero and 1000 years. They affect the rate of release from granite tanks and brine pockets only in those scenarios where the canisters are not destroyed. The longer the canister life, the lower the dose and the smaller the areas contaminated; the differences, however, are relatively small.

In the sensitivity analysis, the leach rate was varied from 10^{-2} per year (yr^{-1}) to 10^{-5} yr^{-1}. Higher leach rates give higher initial doses, but then decrease more rapidly because the amount of waste available for further entry into the aquifer is rapidly depleted by leaching. At very high leach rates, the nuclides are depleted so rapidly that a relatively narrow band of contamination passes through the aquifer.

Nuclide solubility limits the rate at which several elements, notably the transuranic isotopes, leave the repository and enter the water. Because the solubilities of these elements are low in the base case, the rate at which they leave the repository is lower than the rate that would be calculated on the basis of leach rates. If we apply no solubility limits, and use only leach rates in the calculation, the plutonium isotopes dominate doses in the later years, with the result that large areas are contaminated for a long time, and the long term risk to an individual is greatly increased.

The last two parameters varied were environmental transport factors, the groundwater velocity and the retardation factor of the aquifer. The groundwater velocity affects the doses by transporting the nuclides to a given point either more quickly or more slowly. There is also more diffusion with higher velocity. The groundwater velocity and retardation factors together determine whether a nuclide will travel the given distance and therefore produce a dose at that point. Retardation factors have the greatest impact upon the results. High retardation factors not only decrease the spread of nuclides into the groundwater, but also are associated with lower nuclide concentrations in the water, because high retardation results from increased sorption on the rocks.

With high retardation factors, nuclides move so slowly that their concentrations are reduced very much before they travel as much as 20 meters in the aquifer. Significant contamination is limited to a very small portion of the aquifer so that our calculations show no areas contaminated enough to give more than 0.5 rem/yr. When nuclides are not sorbed, so that they move as fast as the water (retardation factor of one), doses are high over very large portions of the aquifer.

Chapter 2
Introduction

2.1 Purpose of the Report

This report addresses the problem of assessing annual doses that might be received by individuals as the result of disposal of high-level radioactive wastes (including spent fuel) in a mined geologic repository. Our attention has been restricted to this particular disposal system because it is further developed than any other and is the only system for which a useable amount of data is available. Consideration of a particular disposal method does not indicate that the Agency favors or endorses that method, but merely that the Agency is trying to establish the potential effects of one system which might be employed.

The assessment of a generic, unbuilt and undesigned disposal system can be made only be modeling. The model we have selected considers the entire disposal system, including the radionuclide content of the waste, engineered barriers, the containment ability of the host rock formation, the geospheric transport pathways, and the biospheric and human transport pathways.

This report is one of three complementary reports presented as support for the Environmental Protection Agency's (EPA) development of generally applicable environmental standards for the disposal of high-level and transuranic radioactive wastes. In it we evaluate the highest annual dose rates that individuals exposed to releases from a deep mined geologic repository might receive. The other two reports describe the population risks in the first 10,000 years from releases from a deep mined geologic repository (SmC 82) and the environmental pathways by which the released nuclides affect people (SmJ 82). In this report we use the same repository, the same environment, and the same release mechanisms used for the population risk report. C.B. Smith, et al. (SmC 82) selected reasonable characteristics for the

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repository system and for the release modes from a spectrum of values given by Arthur D. Little, Inc. (ADL 79). Values were selected that would be achievable by technology or in nature, and that were conservative (i.e., would give larger releases) so that the performance of the repository modeled in the report would probably be poorer than would be expected from an actual repository; SmC 82 gives the justification for the selection of values. Since we have used Smith's values, the doses we calculate in this report are probably higher than those that would be expected from an actual repository. We use only two of the environmental pathways modeled by J.M. Smith, et al. (SmJ 82), drinking water and breathing air. The pathways employed in this report use the same parameters used in SmJ 82.

High-level and transuranic waste disposal systems must isolate these wastes from the accessible environment for a very long time. Most releases of radionuclides would occur as a result of unintentional or unplanned events, either natural or caused by people. We have made our analysis of highest annual individual dose rates for releases initiated in the first 10,000 years. After that time doses to individuals would be lower because of the reduction in quantity of many important radionuclides by radioactive decay.

2.2 Plan of the Report

Chapter 3 is a general description of our analysis of individual doses. We describe the disposal system, including the repository, the wastes, and the environment. We also describe events that can release radionuclides to the environment and select release scenarios at various times in the repository history. In these descriptions, we select values for the characteristics of the wastes and of the disposal system as input parameters for the dose calculations. We also describe the pathways by which radionuclides can reach people and the way in which we calculated the resulting doses.

In Chapter 4, we consider the quantities of radionuclides released by the initiating events and their movement through the environment to people. In Chapter 5 we present the projected annual dose rates that might be incurred by individuals as a result of radionuclide releases from the generic repository with selected characteristics. We also present the extent of contaminated environment. In Chapter 6 we present our calculations of how varying different system characteristics would affect our projections of doses to individuals.

We did not assess the individual doses from every one of the broad spectrum of events that might occur. Instead, we have considered a small subset of all possible events, which we believe span a reasonable range of circumstances and adequately illustrate potential consequences. These events were chosen to include two small releases with a relatively high probability and a larger release with relatively low probability. Each event was examined at four occurrence times, representative of the early period when short-lived fission products are significant, of intermediate periods, and of the later period when the waste is dominated by long-lived fission products and actinides. The analysis addresses the impact on individuals of unplanned, although not unforeseen, events.

We expect that most releases of radioactive material from the repository will be the unintentional result of human intrusion, such as drilling through the repository during a search for resources, or of natural events, such as fault movement. We must include the probability of such releases in our assessment.

We considered radionuclide releases to those portions of the environment that would produce the largest doses to individuals: the groundwater stratum and the land surface immediately overlying the repository. For convenience we will refer to the groundwater strata as aquifers, although they may not produce enough water to serve as sources of drinking water.

The assessment of individual doses from the disposal phase of a waste repository is complicated by the uncertainties in the projected activities of people and in the use of a generic site. These uncertainties are greater than those encountered in the calculation of population doses, where the activities of many people are averaged out. They are also much greater than those encountered in the calculation of dose to the maximum individual from a proposed operation which is intended to continue for a relatively short period of time. Examples of such uncertainties are: (1) whether or not a specific site will be associated with an aquifer suitable for use for drinking water or as a supply of irrigation water, and (2) the probability that an event will open a route to an exposure medium, such as land surface, or (3) the extent of the pathway opened by a specific event.

The probability that some (or a few) individuals may actually receive these doses can be estimated only very roughly. The following material is therefore presented with the caveat that the results merely indicate an upper estimate of doses to individuals.

Chapter 3
Description of the Model

3.1 Introduction

In this chapter we describe the methods we used to assess the doses that individuals might receive. First, we describe the repository, the wastes, and the geospheric environment. Next we discuss the kinds of events that could release radionuclides from confinement and the pathways by which they could reach people. Third, we describe the particular release scenarios we chose for analysis. Finally, we provide the procedures we used for calculating dose and contaminated areas and for estimating the probabilities that people would receive the calculated doses.

3.2 The Disposal System

We made our assessment for a mined geologic repository containing 100,000 metric tons of unreprocessed irradiated (spent) fuel from commercial power reactors. When emplaced, the fuel is contained in 35,000 individual metal containers (canisters). We selected unreprocessed spent fuel as the radioactive waste because it contains both the fission products and the transuranic nuclides produced in the operation of nuclear reactors. The potential hazard from spent fuel is greater than that from an equivalent amount of processed waste, because of the larger transuranium content. Analysis of doses from spent fuel gives information that is useful in assessing doses from processed wastes and from transuranic wastes.

3.2.1 The repositories

The reference repositories are mined cavities in bedded salt or in granite. Each repository is two kilometers wide and four kilometers long (SmC 82). About one-fourth of the repository is mined for the waste, the rest being left as walls and pillars. The mined portion is five meters thick. After the wastes have been placed in the repository, the mined areas are backfilled. We assume that the backfill cannot be refilled to the original density, so that it contains voids amounting to 20 percent of its total volume, or 2,000,000 cubic meters.

In granite, the void volume fills with groundwater moving through fractures in the bulk rock and also through shafts and boreholes (ADL 79). All the water becomes connected throughout the mined volume and the shafts and can be considered as one large volume: the "granite tank".

In the salt repository, the water is expected to enter through imperfections in shaft and borehole seals. Once the salt repository has been closed, the salt begins to flow plastically under the weight of the overlying salt and the other geologic formations, so that most of the void space is eliminated. Only a small amount of the water may remain trapped in the salt in the form of brine pockets. We assume that each brine pocket is in contact with two waste canisters and contains 0.06 m^3 of brine.

The model repository in bedded salt is 460 meters (1500 feet) below the surface. Above and below the repository layer are 50 meters of salt, 50 meters of impermeable rock, and a 30-meter thick porous medium (aquifer). There are 330 meters of undefined sedimentary overburden between the top of the upper aquifer and the surface. The repository in granite is also modeled as 460 meters below the surface. The granite formation continues downward indefinitely, so that there is no lower aquifer. There are 230 meters of granite above the repository, and then an aquifer identical with the one modeled above the salt repository. Above the aquifer are 200 meters of overburden.

3.2.2 The wastes

We assigned the spent fuel a composition of 95.5 percent uranium isotopes, 0.9 percent plutonium isotopes, 0.1 percent other transuranium isotopes, and 3.5 percent fission products (ADL 79). We selected fifteen nuclides as potentially significant contributors to human dose. These nuclides produce large doses for each curie ingested or inhaled, have long half-lives, and are present in the waste in large quantities. We assumed that a period of ten years elapses between removal of the spent fuel from the reactors and its burial in the repository. Table 3.1 lists the significant radionuclides in the waste and their half-lives and initial inventories (ADL 79).

The inventory of most of the nuclides in Table 3.1 at any time may be obtained from the initial inventory by simple radioactive decay calculations. Two nuclides in the list, Am-241 and neptunium-237 (Np-237), are produced from precursor (parent) nuclides in quantities greater than ten percent of their original inventory. Both nuclides are formed in the chain:

We developed an "equivalent initial inventory" of these radionuclides so that their inventory at any time could also be obtained by simple radioactive decay calculations. In order to do this, the initial inventory of Am-241 was increased, atom for atom, by the initial inventory of Pu-241 to give the equivalent initial inventory of Am-241. Similarly, the initial inventory of Np-237 was increased, atom for atom, by the initial inventories of Pu-241 and Am-241. This calculation is conservative in two ways. First, the inventory of each daughter nuclide is increased above the actual value for the period during which it is growing in. Second, for several half-lives of Am-241, the same atom is counted as both Am-241 and Np-237. Adjustment of the inventories of Am-241 and Np-237 in this conservative way permitted use of the equations developed for modeling. The "initial inventory" values of Am-241 and Np-237 in Table 3.1 have been adjusted in this way.

At 200 years after repository sealing, the shortest time used in the calculations, essentially all the Pu-241 has become Am-241, so that this part of the approximation introduces no error. By 1500 years,

Table 3.1
Radionuclide Data

Nuclide	Half-life (Years)	Initial inventory (Curies)
C-14	5.73E+03	5.62E+04
Sr-90	2.88E+01	6.00E+09
Zr-93	9.50E+05	1.87E+05
Tc-99	2.10E+05	1.43E+06
Sn-126	1.00E+05	5.60E+04
I-129	1.70E+07	3.77E+03
Cs-135	3.00E+06	2.23E+04
Cs-137	3.00E+01	8.64E+09
Np-237	2.14E+06	1.21E+05*
Pu-238	8.90E+01	2.19E+08
Pu-239	2.40E+04	3.31E+07
Pu-240	6.76E+03	4.89E+07
Pu-242	3.79E+05	1.74E+05
Am-241	4.58E+02	4.02E+08*
Am-243	7.65E+03	1.72E+06

*Equivalent initial inventory (see Section 3.2.2)

90 percent of the Am-241 has become Np-237, so that the overestimation of the Np-237 introduces a small error into the calculation of doses from this nuclide. The overall effect, however, is very small, because we calculate that Np-237 is a minor contributor to doses before 3350 years.

The persistence of the radioactive material in its solid form is determined by the canister life, the waste matrix leach rate, and the solubility of the nuclide in water. The canisters eventually fail by corrosion in the repository water. We assumed they would last 100 years in the salt repository and 500 years in the less corrosive granite repository water. For convenience in making our calculations, we assumed that all canisters would fail completely at the same time. Once the canisters have failed, the wastes come into contact with any water in the repository and radionuclides begin to enter the water. The maximum rate at which any nuclide can enter the water is determined by the leach rate of the waste, defined as the fraction of material dissolved from the high-level waste matrix during a given period of time. We assigned a value of 10^{-4} per year (SmC 82) for the leach rate. Some nuclides cannot enter the water as rapidly as the leach rate would indicate, because they have a limited solubility in repository water. We assumed that the elements uranium, plutonium, neptunium, and technetium would be present as tetravalent oxides in the repository, and that americium would be present as trivalent oxide. These elements will be in these forms in a chemically-reducing repository environment (SmC 82). Under these conditions uranium, plutonium, neptunium, and technetium are soluble to the extent of one milligram per cubic meter of water (one part per billion) and americium is soluble to the extent of 50 grams per cubic meter of water. With these values, americium concentration is limited by solubility only in the very small quantities of water in brine pockets; plutonium, neptunium, and technetium concentrations are always limited by solubility. Table 3.2 gives the solubility values for each nuclide, expressed as curies per cubic meter.

Table 3.2

Solubility Limits and Retardation Factors

Nuclide	Solubility Limit[1] (Ci/m^3)	Retardation Factors	
		Low Values[1]	High Values[2]
C-14	NA	1	10
Sr-90	NA	1	100
Zr-93	4.1E-06*	10	10,000
Tc-99	1.7E-05	1	1
Sn-126	3.0E-02	10	1,000
I-129	NA	1	1
Cs-135	NA	1	1,000
Cs-137	NA	1	1,000
Np-237	7.0E-07	100	100
Pu-238	NA	100	10,000
Pu-239	6.0E-05	100	10,000
Pu-240	2.2E-04	100	10,000
Pu-242	4.0E-06	100	10,000
Am-241	160	100	10,000
Am-243	10	100	10,000

Notes:

*4.1E-06 = 4.1×10^{-6}.

NA = not applicable, i.e., nuclide concentrations are not limited by solubility.

(1) SmC 82
(2) ADL 79

3.2.3 The environment

Releases to the land surface and to groundwater are the most important routes through which individual doses may be incurred. The highest doses would come from the land surface and groundwater immediately above the repositories. Land surfaces do not have special characteristics that are important in the calculation of maximum individual doses, but groundwater strata do.

One important characteristic of groundwater in the calculation of individual doses is the velocity with which a nuclide moves in the groundwater. Groundwater moves through a porous rock with a velocity that depends on the permeability of the rock, the horizontal gradient driving the flow, and the void fraction or porosity. The velocity is given by the equation (ADL 79):

$$V_i = \frac{K\ i}{\varepsilon} \qquad (3.1)$$

where, V_i is the interstitial velocity,
K is the permeability,
i is the gradient, and
ε is the porosity.

We assumed that we could model the aquifer by an equivalent porous permeable rock, with a porosity of 0.15, a permeability of 31.5 meters per year (10^{-4} centimeter/second), and a horizontal gradient of 0.01 (SmC 82, ADL 79). With these parameters, the interstitial velocity of water in the aquifer is about 2.1 meters per year (m/yr). We also assigned a gradient of 0.01 to the vertical flow between the two aquifers in the bedded salt repository system.

Some nuclides move in groundwater with the same velocity as the water. Others move more slowly because they become attached to rock mineral surfaces and move with the water only while they are not attached. The ratio of the water velocity to the nuclide velocity is called the retardation factor. We used a reference set of conservatively chosen retardation factors (SmC 82). Table 3.2 gives these factors for each radionuclide and also a less conservative set (ADL 79) that we used in testing the effect of changing system characteristics. A radionuclide with a retardation factor greater than one would migrate more slowly than the aquifer water and would have a velocity equal to the aquifer water velocity divided by the retardation factor.

3.3 Initiating Events and Release Modes

Arthur D. Little, Inc. (ADL 79) described a number of failure elements, processes or events that could result in radionuclide release. Table 3.3 lists these in approximate order of decreasing probability. We selected future drilling, fault movement, and shaft seal leakage for analysis. Future drilling represents a rather likely initiating event that would release small quantities of the waste. Fault movement represents a rather unlikely event that would release larger quantities of radioactive material. Shaft seal leakage is an expected process that releases quantities of the waste similar to those released by drilling.

We did not consider other events for one of two reasons. First, some events are very unlikely, although their consequences might be very high. We omitted vulcanism, meteorite impact, and igneous intrusives for this reason. Their probabilities of occurring, in any reasonably well-selected location, are so small that we do not believe they should be a basis for regulatory action. The other reason for eliminating some initiating events is that the doses that would be associated with them are similar to, or less than, doses from the events that we did consider. We eliminated releases through boreholes sealed during repository construction, through undetected pre-existing boreholes, and through bulk rock because we believe the resulting doses would be no greater than those from future drilling. We believe repository builders, knowing the dangers of the waste materials and operating under strict regulation, will seal their boreholes better than people drilling for resources in the future would. Undetected pre-existing boreholes would most probably be in the unmined portion of the repository; otherwise they would be detected. They would therefore not be in direct contact with the wastes and releases through them would be small. The radionuclides released by flow through bulk rock,

Table 3.3

Failure Elements and Associated Probabilities

Failure Element	Annual Probability of Occurence	
	for repository in bedded salt	for repository in granite
Expected Processes		
Flow through bulk rock	0	1
Shaft seal leakage	1	1
Borehole seal leakage	1	1
Unplanned Events		
Undetected boreholes	3E-03	3E-03
Future drilling(1)		
into repository	0.02	2.5E-03
direct hit on waste	2E-05	2.5E-06
Breccia pipe		
first 500 yr after sealing	0	0(2)
beyond 500 yr	1E-08	0(2)
Fault movement	2E-08	2E-08
Volcano	1E-10	1E-10
Igneous intrusives	2E-10	1E-10
Meteorite impacts	4E-11	4E-11

Notes:

(1) Primarily from resource exploration

(2) Breccia pipes do not develop in granite; they are the result of deep dissolution processes in bedded salt which can lead to collapse of overlying material (ADL 79).

although probably somewhat larger in total amount than those released through a future borehole, would be released through the entire aquifer and so the concentration would nowhere be as high as that from a borehole. Finally, we did not consider release through a breccia pipe because the releases would probably be smaller than those from faulting, and the probabilities are more or less the same.

The pathways created after the events considered lead to two release points--the land surface and an aquifer (ADL 79). We omitted releases directly to air, which occur only as a result of events with extremely low probabilities, such as meteorite impact and volcanic activity. We also omitted pathways to surface water because it would not be difficult to avoid repository sites where the hydraulic pressure in the groundwater system, projected over conditions in the 10,000 years following repository sealing, would not be artesian--that is, it would not be high enough to bring groundwater to the surface spontaneously.

We considered that radionuclides in groundwater reached people only when they drank water. We assume that a regulatory agency will reject sites where the groundwater formation would produce enough water to be useful for irrigation within the first 10,000 years after repository sealing.

The model aquifer is a very poor producer of water. The capacity of an aquifer to deliver water through a well is given approximately (Ha 62) by the equation:

$$Q = \frac{2\pi K_a m(\Delta h)}{\ln(r_e/r_w)} \tag{3.2}$$

where, Q is the volume flow of well water (m^3/yr),

K_a is the permeability of the aquifer (m/yr),

m is the thickness of the aquifer (m),

Δh is the hydraulic head (m),

r_e is the radius of influence (m), and,

r_w is the radius of the well (m).

With the aquifer values given in Sections 3.2.1 and 3.2.3, a well radius of 0.1 meter (m) (4 inches), an assumed radius of influence of 1000 m, and a h value of 3.3 m, corresponding to a depth of 330 m and a gradient of 0.01, the sustainable flow would be 2100 m^3/yr. If this were used for irrigation at a rate of 0.75 m/yr (about 30 inches), it would serve 2800 m^2, which is somewhat less than one acre. We therefore did not include doses from eating irrigated foods in these calculations. Radionuclides released to the land surface were considered to reach people when they breathed air contaminated with resuspended nuclides.

3.4 Release Scenarios

3.4.1 Drilling for resources

We postulated that a hole with a cross-sectional area of 0.1 m^2, corresponding to a diameter of 0.36 m (14 inches), is drilled through the repository strata during exploration for resources, connecting the repository to the upper aquifer and to the land surface. In bedded salt, the hole also connects the repository to the lower aquifer. We assume that the drillers reseal the hole to a permeability of 31.5 m/yr (10^{-4} cm/sec) (ADL 79). This permeability value represents relatively poor sealing that might be expected from drillers who are unaware of the hazard of the radioactive wastes. We assumed that the drillers would abandon and reseal the hole if they do not discover any resources. If they do discover resources, we assumed they would exploit these through an opening sealed from any permeable stratum, and that they would reseal the hole as described above after the resources had been used.

Release to the aquifer

Release of radionuclides to groundwater is a slow, continuing process. Leaching and dissolution slowly remove radionuclides from solids, and low flow rates slowly transfer repository water into the aquifer. Slow movement of radionuclides in the aquifer, combined with slow releases into the aquifer, result in a gradual increase in the amount of nuclides in the groundwater, with maximum doses at any point generally occurring many years after the initiating event.

Movement of water in a porous geologic stratum is controlled by convection and diffusion; for each nuclide introduced at a single point, the subsequent concentration varies with space and time. Upon reaching an aquifer, the nuclide moves downstream from its point of origin (the borehole). Simultaneously, it spreads transversely across the aquifer, contaminating a parabolically-shaped area. At some future time, according to our hypothesis, an individual may unknowingly drill a well within the contaminated area to obtain drinking water. Our goal is to estimate the dose which this individual would receive from drinking the contaminated aquifer water. Because each nuclide diffuses at its own rate, depending on the extent to which it is adsorbed by the aquifer minerals, the description of the system is very complex.

We developed two scenarios involving releases to the aquifer by drilling, under the assumption that they would be representative of those release modes having potentially severe consequences for individuals. In the first scenario, we postulated that the waste from a single canister is penetrated. Since we assume that the canisters are emplaced five meters apart and the drill has a diameter of 20 centimeters (ADL 79), we conclude that the drill cannot strike waste from two separate canisters. The drill continues downward at least until it strikes the underlying aquifer, if any. In both of our repositories, the upward flow of water to the aquifer is driven by the heat produced by the decay of the radioactive waste, which sets up a thermal buoyancy gradient. In salt there is another driving force, the connection of the underlying aquifer with the overlying aquifer, which produces an hydraulic gradient. We assume, for conservatism, that the hydraulic gradient is upward and therefore adds to the buoyancy gradient. The rate of water flow to the aquifer is proportional to the total upward gradient and to the permeability and flow area of the borehole. The water removes a fraction of the waste nuclides and carries them up into the overlying aquifer.

In the second scenario, we assume that the canisters have failed prior to the initial drilling operation, and that their contents have been partially leached and dissolved into a brine pocket in a bedded salt repository, or into the granite tank. We postulated that some repository water moves to the aquifer with the groundwater flow. We present the equations for both scenarios in Section 4.1.

Release to the land surface

Radioactive material may also be brought directly to the land surface by drilling, and then dispersed into the atmosphere. The drill may either hit waste directly or may penetrate the water volumes surrounding the wastes in the repository, as described above. A direct hit on the waste moves a fraction of the material directly to the land surface. We assumed that this fraction was 15 percent of the contents of one canister (ADL 79). Similarily, when a drill penetrates into the repository water, it brings some of this water directly to the land surface. We assumed that 200 m^3 would be brought to the land surface from a granite repository and that the entire contents, 0.06 m^3, of one brine pocket would be released to the surface from a salt repository (ADL 79). The entire contents of the brine pocket reach the surface because the pocket is under pressure from the overlying geologic formations.

The waste material brought to the surface may be disposed, it may be covered by other residue from the borehole, or it may lie on top of the residue pile. The latter provides the most conservative estimate. The material is assumed to be a point source. We did not calculate the direct radiation dose from this release, which may be very large, because it depends on the way the material is handled, on the length of time the drillers are exposed, and on other incident-specific factors; also, since in all likelihood only the drillers would be involved, and not the general public, we did not consider this accident to be pertinent to this work. We did calculate the consequences to those individuals who inhale airborne radioactivity at various distances from the borehole and various times after the event. It is not likely that these exposures can be avoided once the waste material has been suspended in the atmosphere. We discuss transport of the released nuclides in Section 4.3.

3.4.2 Faulting

Faulting can dramatically change the permeability of the host rock and provide a pathway for release of radioactive material to the overlying aquifer. The faulting event is postulated to open communication between the repository and an aquifer along a line that runs the full length of the repository, thus involving a larger amount of waste than drilling. The faulting event does not release radionuclides to the land surface, since we assume the regulatory agency would not permit selection of a site where the supply aquifer is under such pressure as to be artesian.

As in the case of drilling, the flow of water to the aquifer is driven by the heat produced by decay of the radioactive waste, and, in salt, also by the hydraulic gradient between the underlying and overlying aquifers. The rate of water flow to the aquifer is proportional to the upward gradient, permeability of the host rock and overlying strata, and the flow area of the fault, unless flow is limited by the ability of the aquifer to provide water.

Arthur D. Little, Inc. (ADL 79) described a faulting event that opened a space one meter wide filled with rubble across the entire extent of the repository. In our analysis, we considered that the zone would affect a 10-meter wide space. The fault could cross the aquifer in any direction. A fault in the direction of the aquifer flow would produce the highest individual doses, because wastes from several individual canisters along the fault would reach a point where dose is measured. A fault across the aquifer would produce lower maximum doses, but might cause contamination of a greater area. The consequences of faults at intermediate angles would fall between those of the faults along and across the aquifer. The fault in the direction of the aquifer was selected for examination because it would produce the highest individual doses. We considered two faulting scenarios.

In one, the fault strikes and breaks a row of canisters; in the other, canisters have failed before the fault develops and the contents of two or more rows of failed canisters are combined in a tank. Only the releases from a fault intersecting water in the granite tank are presented here, since they are much larger than releases restricted to direct effects on canisters.

As in the case of a drilling release from a granite tank (Section 3.4.1), the rate of entry of a radionuclide into the aquifer is determined by the concentration of the radionuclide in the tank and by the flow rate of water into the aquifer, in this case through the fault. For large faults, the flow is limited by the capacity of the aquifer to receive water, not by the capacity of the fault to transmit it. This limit is about 18,000 m^3/yr, which is about one percent of the volume of the granite repository water. Approximately one percent of the contents of the repository tank, therefore, are brought to the aquifer every year. The concentration of nuclides in the tank increases with time after canister failure. A detailed mathematical discussion of the movement of radionuclides into and through the aquifer after faulting is provided in Section 4.2.

3.5 Dosimetry

We calculated the annual dose equivalent (hereafter referred to as dose) rate to red bone marrow, in rem per year (rem/yr), to individuals from drinking contaminated water. We also calculated the annual dose rate to the lungs of individuals from breathing contaminated air. We did not assess exposure to direct radiation from contaminated surfaces or from submersion in the atmosphere because they are small compared to doses from drinking water and breathing air. Use of the annual dose rate facilitates comparison with the limits for individual dose in other EPA regulations such as those for operations in the uranium fuel cycle (40 CFR 190) and for drinking water (40 CFR 141) and in Federal guidance.

Calculating the annual dose rate to a single organ underestimates total risk to an individual. We believe this underestimation, for these bone-seeking nuclides, is less than a factor of two. This underestimation, considering the uncertainties in the input parameters to the calculation, would not change the decisions made in the regulation. Methods for calculating total risk to an individual were not available when we made these calculations.

For both ingestion and inhalation, the dose equivalent rate, H'_{jik}, to organ k from nuclide i via pathway j can be expressed as:

$$H'_{jik} = c_{ji}\ U_j\ D_{jik} \tag{3.3}$$

where, c_{ji} is the concentration of the i'th nuclide in the j'th medium,

U_j is the annual intake of the j'th medium, and

D_{jik} is the dose equivalent conversion factor (rem/curie) for the i'th nuclide by the j'th pathway to the k'th organ.

Table 3.4 gives the dose equivalent conversion factors (DECF) used for inhalation and ingestion of selected nuclides. The values of D_{jik} were obtained from Killough et al (Ki 78) and Dunning et al (Du 79). They give these DECF's for 22 target organs expressed as 50-year dose commitments from the intake of one curie. These values are also the annual dose rates in the 50th year from chronic intake at a level of one curie per year for fifty years (ICRP 59).

There are three pertinent DECF's for a nuclide, one for ingestion and two for inhalation. The DECF for ingestion is designated by D_{wik}, and those for inhalation by D_{bik}.

3.5.1 Choice of organs

We calculated the annual dose rate to red bone marrow for ingestion and lung for inhalation for each nuclide and then summed over the fifteen nuclides. We selected red bone marrow as the primary organ of interest for ingestion because there is a large risk per rem for this organ and because many of the nuclides of interest are "bone seekers." (Ce 69).

We selected the lungs as the primary organ of interest for inhalation. When waste is released directly to the land surface by a direct hit it is transported as is in a relatively insoluble form. The proper model for inhalation is therefore uses the most insoluble form, i.e., Class Y (Table 3.4). For any nuclides that do not have Class Y DECF's, we used the class giving the highest DECF, usually Class W. When waste is released to the land surface by drilling into repository water, the nuclides are usually soluble. We selected appropriate retention classes, using the discussions of Killough (Ki 78). In case of doubt as to the appropriate class, we used the more conservative (higher dose) values. We selected a particle size of one micrometer activity median aerodynamic diameter (AMAD) for all inhalation dosimetry.

3.5.2 Annual dose rates from drinking water

Equation 3.4 gives the annual dose rate associated with drinking water having any radioactivity concentration. The value of U_j for ingestion of water is given as 1.65 liters per day (ICRP 75), or $0.60\ m^3/yr$. The annual dose rate from drinking water can therefore be expressed as:

$$H'_{wik} = 0.60\ c_{wi}\ D_{wik}. \tag{3.4}$$

The concentration, c_{wi}, is obtained from equations 4.41, 4.43, 4.45, or 4.47 when the nuclide reaches the aquifer through a small channel, and from equation 4.52 or 4.54 when it is introduced over the entire area due to faulting. If c_{wi} is in Curies per cubic meter (Ci/m^3), H'_{wik} is in rem/yr.

3.5.3 Annual dose rates from inhalation

Individuals may receive a dose as a result of inhaling wind-blown radioactive material suspended in the atmosphere following a release from the repository directly to the land surface. Once the air concentrations, X_i, have been obtained, the dosimetry is:

$$H'_{bik} = D_{bik}\ U_b\ X_i \tag{3.5}$$

where, D_{bik} is the inhalation DECF for nuclide i (rem/Ci),
U_b is the breathing rate (m^3/yr) and,
X_i is obtained from equation 4.55.

Table 3.4
Dose Equivalent Conversion Factors
(rem/Curie)

Nuclide	Ingestion Bone Marrow	Inhalation Class Y Lung	Inhalation Class W Lung
C-14	3.40E+03	6.18E+00	6.18E+00
Sr-90	4.30E+05	8.54E+06	4.92E+04
Zr-93	3.00E+02	5.85E+04	3.08E+04
Tc-99	3.20E+02	5.22E+04	5.22E+04
Sn-126	8.60E+04	1.27E+06	1.27E+06
I-129	9.40E+02	7.88E+02	7.88E+02
Cs-135	1.10E+04	6.40E+02	6.40E+02
Cs-137	7.40E+04	1.62E+04	1.62E+04
Np-237	6.20E+06	2.90E+08	3.00E+07
Pu-238	1.70E+05	3.09E+08	3.20E+07
Pu-239	1.90E+05	2.94E+08	3.00E+07
Pu-240	1.90E+05	2.95E+08	3.10E+07
Pu-242	1.80E+05	2.80E+08	2.90E+07
Am-241	6.40E+06	3.13E+08	3.20E+07
Am-243	3.20E+07	3.03E+08	3.10E+07

3.6 Method of Calculating Dose

We calculated the dose to a person at preselected times and places. By the very nature of the digital computer, the calculations must be done at discrete points. We limited the number of calculations both to save computational time and to keep the output to an amount we could present in a readable format. We selected times from 10 to 10,000 years after the event. In addition to the decade values of 10, 100, 1000, and 10,000 years, we calculated for the intermediate times 20, 50, 200, etc. We started the calculation of annual dose rates ten years after the drilling release and twenty meters from the drilling point. Doses incurred earlier than 10 years after the release do not differ significantly from those at 10 years because the long-lived nuclides involved decay only slightly in that time.

For releases to groundwater from drilling, we selected distances from 20 to 4000 meters downstream from the point of introduction, the borehole. We calculated the dose due to each nuclide at the preselected time and distance, and then summed over all nuclides. These calculations give the dose to a person who drinks water from the aquifer at the preselected time and distance. We did not calculate annual dose rates at distances less than 20 meters from the borehole because such calculations would not be representative of doses received by drinking the water. Wells draw water from a considerable area of an aquifer. A well drilled close to the borehole would be drawing water from an area including some uncontaminated areas upstream of the borehole. The probability that a well would be drilled in the area between the borehole and 20 meters away is small. We also calculated, for each preselected time, the area that would be sufficiently contaminated to cause a person who drinks the water to incur a dose above a specified level, e.g., 0.5 rem/yr. We did this by calculating the transverse distance, y, for each preselected distance, x, at which the dose would equal the preselected dose level. The set of x and y values defines an area contaminated to the specified dose level. This area was approximated by a set of trapezoids symmetrical about the x-axis.

For releases from faulting, we also selected distances from 20 to 4000 meters. These distances, however, are from the upstream boundary of the repository, since there is no introduction point, but instead a release all along the length of the repository.

For the land surface releases due to drilling, we also calculated the dose at preselected times and places. In this case, since all the nuclides move in the same way in space, we calculated the area contaminated at any given time simply from the distance to which the specific level of contamination had reached.

3.7 Event Times

To facilitate the analysis of individual dose over the 10,000-year time span, we divided the time into four periods as follows (midpoints shown in parentheses): 100-300 (200), 300-1700 (1000), 1700-5000 (3350), and 5000-10,000 (7500). These periods are dominated, in general, by the short-lived fission products, by Am-241, by Am-241 and Am-243, and by Am-243 and Pu-239, respectively. Because it is impractical to calculate individual doses for all possible event times, the midpoints are taken as the event times; we assumed they are representative of their respective periods with regard to the expected consequences of the various release scenarios. We made no calculations for events after 10,000 years, because the reduced inventories would result in substantially lower doses than would be incurred from events prior to 10,000 years.

3.8 Risk and Probability

The risk that the radioactive waste presents to any individual depends not only on the dose levels to which a person would be exposed, but also on the probability that the person will actually incur them. The important factors affecting this probability are:

1. the likelihood that the contaminating event will occur; and
2. the likelihood that one or more individuals will be exposed to the contaminated medium.

The second likelihood, in turn, depends on the quantity of the medium that is contaminated and on the extent to which the medium is used.

3.8.1 Probability of contamination

Drilling

We assumed a 100-year period of institutional control, during which there would be no drilling. Arthur D. Little, Inc. (ADL 79) postulates that after the initial 100 years, there would be drilling somewhere in the repository area, once every 50 years in bedded salt, or once every 400 years in granite. The drills would either strike waste directly or would penetrate into the repository water. Drilling into the repository water produces most of the risk from drilling, since direct hits on waste are much less likely than penetrations into repository water (ADL 79).

The Arthur D. Little drilling frequency estimates are very imprecise, as are all predictions of future human activity. Nevertheless, the probability of some drilling intrusions into any repository seems to be high. For modeling purposes, we may assume that drilling will contaminate the aquifer.

Faulting

Fault movement, in contrast to drilling, is an unlikely event. Arthur D. Little (ADL 79) has given a postulated annual frequency of fault movement of 2×10^{-8} (once in 50 million years) for a repository in either bedded salt or granite. Hence, the likelihood of a fault in 10,000 years is about 0.02 percent.

3.8.2 Probability of exposure

Releases to the land surface

The extent to which people are exposed to this source of radiation depends on how many people use the land and, to some extent, on the way in which it is used. For the purposes of this generic evaluation, we use the average world population density of 6.7×10^{-5} people per square meter (SmJ 82), a value somewhat higher than most other population densities. For example, the rural U.S. population in 1970 was about 54,000,000 while total farm acreage was 1,066,000,000 (Wo 77). The corresponding population density is 1.25×10^{-5} people per square meter. Population density of the contiguous United States is 2.6×10^{-5} people per square meter. Regional U.S. values range from 1.2×10^{-5} in the West to 12×10^{-5} in the Northeast.

Releases to the aquifer

The extent to which people will be harmed by releases to aquifers depends on the doses they would incur by using the aquifer water, the amount of the aquifer contaminated, and the extent to which the aquifer water is used. The extent to which the water is likely to be used depends on the population density in the area and the availability of other water sources for that population. We do not know either of these factors, because we cannot predict future populations and we do not know what location will be selected for the repository. We estimated a general probability that a well will be drilled in an aquifer similar to the one modeled in this report, using the frequency of water well drilling in the United States. We calculated in Section 3.3 that a well drilled in our aquifer would produce a sustainable flow of 2100 m^3/yr, about one gallon per minute. We found (NW 79) that about one-half of one percent of the 500,000 water wells drilled annually (Ge 73) yielded less than ten gallons per minute and were more than five hundred feet deep. We doubled the frequency to one percent, or 5000 wells per year, to allow for possible greater use of groundwater in the future. If these wells were drilled uniformly in the 7.8×10^8 hectares of the United States, there would be 6.4×10^{-6} wells per hectare per year. We used this frequency, based on shallower, more productive aquifers than our model, as a conservative estimate for the frequency of drilling into our aquifer.

There is a fairly high probability, over a long time, of one or more wells being drilled into an aquifer that is contaminated for a long time. For example, if we use the frequency of 6.4×10^{-6} wells per hectare per year for 10 hectares contaminated for 10,000 years, there is about a 47 percent probability that at least one well will be drilled into the contaminated area sometime in the 10,000 years.

Although the probability over a long time of drilling a well into a contaminated aquifer is high, the risk is spread over all the people living during this time, with a smaller risk to any individual. For a general estimate of the risk to an individual we use the probability per hectare of drilling into the aquifer during a seventy-year lifetime. The frequency of drilling then becomes $(70) \times (6.4 \times 10^{-6})$ or 4.5×10^{-4} per hectare.

Chapter 4
Radionuclide Release and Transport

We divided our model for annual dose rate calculations into three stages: (1) releases from the repository, (2) concentrations in the environment, and (3) ingestion or inhalation of radionuclides by exposed individuals. Stage three was covered in Section 3.5. In this section, we develop equations that describe the processes of stages one and two.

The representative release events we analyzed are (1) releases to the aquifer due to drilling and subsequent borehole seal degradation, (Section 4.1), (2) releases to the aquifer due to faulting, (Section 4.2), and (3) direct releases to the land surface (Section 4.3).

4.1. Release to the Aquifer due to Drilling

In this set of scenarios we considered resource exploration only within the physical boundaries of the repository and drilling events through the upper aquifer, through the repository, and into the lower aquifer, in the cases where one exists. We expect groundwater to flow through the resulting borehole into the upper aquifer. If no lower aquifer exists, as in the granite repository, the flow is induced entirely by thermal buoyancy. Where there are both an upper and a lower aquifer, as in the bedded salt repository, we conservatively assume that an upward hydraulic gradient exists between them and adds to the thermal gradient. We expect part of the radionuclide inventory contained in the repository to be either dissolved or leached and transported by this groundwater flow to the upper aquifer.
We examined two drilling scenarios: (1) penetration into the waste in a single canister and (2) penetration into repository water containing waste dissolved or leached from failed canisters. The mathematical treatments of the release rates are described in the following section. The subsequent transport of released radionuclides through the aquifer is the subject of Section 4.1.2.

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4.1.1 Release rate from the repository

Radioactive material is released from the repository following dissolution of waste radionuclides by repository water. The rate of removal of a radionuclide from the solidified waste into the repository water may be governed by the leach rate. Some radionuclides cannot be dissolved as readily as the leach rate would allow, because their solubility in the water is limited. In addition to leach-limited and solubility-limited release rates, we also consider the case where the entry of each nuclide into the repository water was limited by the dissolution of the uranium dioxide (UO_2) that constitutes the waste matrix for spent fuel. The UO_2-limited case is a special form of the leach-limited case.

Direct hit on waste: Leaching governs release

The quantity of a nuclide at any time t after disposal of the waste in the repository is given by the initial inventory, Q_0, corrected for radioactive decay to time "t". All equations refer to individual nuclides unless otherwise specified.

The inventory available for release at the time of the event, $t = t_e$, is:

$$Q(t_e) = fQ_0 \exp(-\lambda t_e) \qquad (4.1)$$

where λ is the decay constant, and the factor f is the fraction of the waste affected by the drilling. Leaching and, therefore, radionuclide release from the waste begin when the drilling occurs, so the inventory is multiplied by the leaching constant, L, to give the quantity of nuclide that leaves the repository per unit time, Q'(t), where $t \geq t_e$,

$$Q'(t) = fLQ_0 \exp(-\lambda t). \qquad (4.2)$$

It should be noted that equation 4.2 has not been corrected for depletion of the waste by leaching during the time it is exposed to water. To make this correction, we assume, in our model, that there is no leaching prior to the time $t = t_e$. This is not strictly true, since some radioactive material may leach into the repository water if the canisters fail before the drilling, but the assumption simplifies the calculation. When we make this correction for leaching depletion, we obtain:

$$Q'(t) = fLQ_0 \exp[-\lambda t] \exp[-L(t - t_e)]. \quad (4.3)$$

<u>Direct hit on waste: Radionuclide solubility governs release</u>

When the quantity of water contacting the waste is sufficiently small, the release rate calculated according to equation 4.3 is overestimated for certain nuclides, because the concentrations of these nuclides are limited by their solubility.

The release rate of a solubility-limited nuclide is given by the equation:

$$Q'(t) = S\,F(t) \quad (4.4)$$

where S is the solubility, Ci/m^3, the values appear in Table 3-2 and,
F is the flow rate, m^3/yr.

The flow rate is the product of the cross-sectional area of the resealed borehole, the permeability of the material used in sealing, and the gradient driving the flow:

$$F(t) = A\,K(t)\,i(t) \quad (4.5)$$

where A is the area of the borehole, m^2;
K(t) is the borehole permeability, m/yr; and
i(t) is the hydraulic gradient.

Therefore, the release rate for solubility-limited nuclides is a combination of equations 4.4 and 4.5:

$$Q'(t) = S\,A\,K(t)\,i(t). \quad (4.6)$$

The permeability may increase with time as the borehole seal degrades, allowing a larger flow of contaminated water to reach the aquifer. The equation describing the permeability as a function of time is:

$$K(t) = K_0 + [(K')(t - t_e)] \quad (4.7)$$

where K_0 = initial permeability, (m/yr),
K' = rate of change of permeability (m/yr^2),
t = time elapsed after repository sealing (yr),
t_e = event time and,
$t \geq t_e$.

The quantity $(t - t_e)$ represents the period over which the borehole seal degrades. Degradation begins when the borehole is resealed, following the release event at t_e. We assume that the flow through the sealing material begins at t_e, and continues until time t.

The gradient, i(t), in equation 4.5 was derived empirically (ADL 79, SmC 82). It describes the change in the gradient between repository and aquifer as a function of time:

$$i(t) = a \exp(-\alpha t) + b \exp(-\beta t) + c. \qquad (4.8)$$

The first two terms in equation 4.8 describe the gradient caused by the thermal buoyancy. These terms also include the effect of temperature on the viscosity of the water. They both decrease exponentially over time, beginning at repository closure. The last term, c, is the hydraulic gradient between the lower and upper aquifers. For granite, this term is zero, because there is no lower aquifer.

Including the terms in equations 4.7 and 4.8 in equation 4.6 we arrive at:

$$Q'(t) = SA[K_0 + ((K')(t-t_e))] [a \exp(-\alpha t) + b \exp(-\beta t) + c]. \qquad (4.9)$$

Direct hit on waste: Uranium solubility governs release

The third possible mechanism of radionuclide release, which is less conservative, postulates that the removal of most of the nuclides is limited by the solubility of the UO_2 matrix in which the waste is interred. Four radionuclides can diffuse through the UO_2 matrix, and so their entry into water is controlled by their own leaching rates. These radionuclides are C-14, Cs-135, Cs-137, and I-129.

To calculate the rate of removal of the other eleven nuclides, the solubility of U-238 (g/m^3) is multiplied by the volume flow rate of the water (m^3/yr) and divided by the total mass of U-238 (g) exposed to the water:

$$L_u = \frac{s_u F(t)}{f M_u} \qquad (4.10)$$

where s_u is the solubility of uranium, g/m^3,

F(t) is the flow rate passing through the affected fraction of the repository, m^3/yr, f is the fraction of the repository affected and,

M_u is the total mass of uranium emplaced in the repository, g.

L_u replaces L in equation 4.3 if uranium oxide solubility is assumed to control the rate of removal, so that the rate at which a nuclide is released is:

$$Q'(t) = \frac{s_u\ F(t)}{M_u} Q_o \exp(-\lambda t) \exp[-L_u(t - t_e)]. \qquad (4.11)$$

We used the approximation:

$$Q'(t) = \frac{s_u\ F(t)}{M_u} Q_o \exp(-\lambda t) \qquad (4.12)$$

because L_u $(t - t_e)$ is always very small compared to the radioactive decay factor times dt.

Brine pocket

When a drill strikes a brine pocket, we assume that the entire contents are released directly to the land surface quickly (see section 4.3.2). From that time on, water from the lower aquifer flows through the brine pocket at a rate of a few brine pocket volumes per year (SmC 82). This water contacts the radionuclides in the waste and releases them to the aquifer in the same way that water contacts waste after a direct hit (Section 4.1.1). Therefore, equations 4.3, 4.4 and 4.10 are applicable to the brine pocket releases.* The value of "f" in equations 4.3 and 4.10 must be adjusted to allow for the assumption that the waste in two canisters is associated with each brine pocket (ADL 79).

Granite tank: Leaching governs release

When the canisters fail, nuclides begin to be leached and dissolved into the repository water. The rate at which a nuclide that

* We treated the brine pocket release more rigorously in the computer calculations by solving the differential equations of section 4.1.1 with a non-zero value of F/V. This rigorous treatment made no difference in the calculated concentrations and doses. We present the treatment in this section as a more easily understood method.

is not solubility-limited dissolves in repository water at any time, t, is given by:

$$dQ_w/dt = LQ_s(t) - [\lambda + F(t)/V]\, Q_w \qquad (4.13)$$

where the subscripts "w" and "s" refer to water (dissolved) and solid (undissolved) phases, respectively, and V is the volume of repository water.

The rate at which the nuclide leaves the undissolved waste is given by the differential equation:

$$dQ_s/dt = -(\lambda + L)\, Q_s. \qquad (4.14)$$

Before the canisters fail, i.e., $t < t_c$, there is no leaching into the tank, and L = 0. Likewise, before the drilling opens a borehole through the repository, i.e., $t < t_e$, there is no flow, and F = 0. For all realistic cases involving drilling, F(t)/V is very small (i.e., a very small fraction of the total granite tank is replaced each year), and we can use the approximation F(t)/V = 0 in equation 4.13.

The solutions of equations 4.13 and 4.14, for the period before canister failure ($t \leq t_c$) are, respectively:

$$Q_s = Q_o \exp(-\lambda t) \text{ and,} \qquad (4.15)$$

$$Q_w = 0. \qquad (4.16)$$

For the period when $t > t_c$, the solutions are:

$$Q_s(t) = Q_o \exp(-\lambda t_c)\exp[-(\lambda + L)(t - t_c)] \text{ and,} \qquad (4.17)$$

$$Q_w(t) = [Q_o \exp(-\lambda t)][1-\exp(-L)(t - t_c)]. \qquad (4.18)$$

The rate of entry of a nuclide from the repository water to an aquifer is:

$$Q'(t) = F(t)\, c(t) \qquad (4.19)$$

where c(t) is the concentration of the nuclide dissolved in the repository water, which is $Q_w(t)/V$. Therefore,

$$Q'(t) = [F(t) \frac{Q_o}{V} \exp(-\lambda t)][1 - \exp(-L)(t - t_c)] \qquad (4.20)$$

where F(t) is given by equation 4.5.

Granite tank: Solubility governs release

When the canisters fail and other geologic characteristics are appropriate, nuclides dissolve in the repository water until they reach their solubility limit. The concentration of solubility-limited nuclides in the repository water is simply equal to the solubility. The rate of their entry into the aquifer is then given by equation 4.4:

$$Q' = S\ F(t) \tag{4.4}$$

where F, the flow rate, is determined by borehole area, permeability, and gradient, as described in equations 4.5, 4.7, and 4.8.

Granite tank: Uranium oxide solubility governs release

As in the case of a direct hit, this case is similar to leaching-governed releases, so that equation 4.20 applies with L replaced by L_u from equation 4.10 for all nuclides except C-14, Cs-135, Cs-137, and I-129.

4.1.2 Transport in the aquifer

The radionuclides introduced into the upper aquifer will be transported downstream by the groundwater flow in that aquifer. The following paragraphs describe the derivation of the rate of radionuclide transport resulting from the drilling release event. Transport is two-dimensional because we assume nuclides are introduced uniformly throughout the thickness of the aquifer. There is no vertical transport because there is no concentration gradient in this direction.

Basic equation

The basic two-dimensional differential equation for the transport of a nuclide in groundwater is:

$$k\,\frac{\partial c}{\partial t^*} - [\nabla \cdot (\overline{\overline{D}} \cdot \nabla c\,)] + [\nabla \cdot (vc)] + \lambda k c = 0 \tag{4.21}$$

where k = retardation factor,
c = concentration of radionuclide in the solution,
t^* = time since radionuclide reached aquifer,
∇ = vector operator,
$\overline{\overline{D}}$ = hydrodynamic dispersion tensor,

λ = radionuclide decay constant and,
v = interstitial velocity of the groundwater flow.

For two-dimensional dispersion in a one-dimensional background groundwater flow (in the x-direction), equation 4.21 can be rewritten as:

$$\frac{\partial c}{\partial t^*} - \left(\frac{D_x}{k}\right)\frac{\partial^2 c}{\partial x^2} - \left(\frac{D_y}{k}\right)\frac{\partial^2 c}{\partial y^2} + \left(\frac{v_x}{k}\right)\frac{\partial c}{\partial x} + \left(\frac{v_y}{k}\right)\frac{\partial c}{\partial y} + \lambda c = 0. \qquad (4.22)$$

In this equation, v_x and v_y denote the vector sum of the velocity components due to the background groundwater flow and the radial flow from the borehole, and are a function of distance. D_y and D_x are the transverse and longitudinal dispersion coefficients expressed in m^2yr^{-1}.

The solution of equation 4.22 is extremely complicated. It is apparent, however, that the component of flow velocity due to the radial flow is significant only in the immediate vicinity of the borehole, and becomes negligible as distance from the borehole increases. When the radial flow effect is negligible and the positive x-axis is chosen to be in the direction of the normal groundwater flow, the equation can be greatly simplified by setting $v_x = v$ and $v_y = 0$, where v is the interstitial flow velocity of the groundwater.

With these assumptions, we can write equation 4.22 as:

$$\frac{\partial c}{\partial t^*} - \left(\frac{D_x}{k}\right)\frac{\partial^2 c}{\partial x^2} - \left(\frac{D_y}{k}\right)\frac{\partial^2 c}{\partial y^2} + \frac{v}{k}\frac{\partial c}{\partial x} + \lambda c = 0. \qquad (4.23)$$

Convective transport is predominant over diffusion in the direction of flow, i.e.:

$$\frac{v}{k}\frac{\partial c}{\partial x} >> \frac{D_x}{k}\frac{\partial^2 c}{\partial x^2}. \qquad (4.24)$$

By using this approximation, we overestimate the highest individual doses and the size of the area contaminated to very high levels; we underestimate the size of the area contaminated to lower levels. Therefore, equation 4.23 may be further simplified by neglecting the dispersion term in the x-direction:

$$\frac{\partial c}{\partial t^*} - \left(\frac{D_y}{k}\right)\frac{\partial^2 c}{\partial y^2} + \frac{v}{k}\frac{\partial c}{\partial x} + \lambda c = 0. \qquad (4.25)$$

The above equation is to be solved with the initial condition:

$$c = 0 \text{ when } t^* = 0.$$

Nuclides are introduced into the aquifer only at the point ($x = 0$, $y = 0$) at a rate $Q'(t)$ where Q' is the release rate of the appropriate radionuclide from the repository as given by equations 4.3, 4.4, and 4.12, as appropriate.

Solution of transport equation

We solved equation 4.25 by superposition. First, we obtained transverse dispersion, by solving the equation:

$$\frac{\partial c^*}{\partial t^*} - \left(\frac{D_y}{k}\right) \frac{\partial^2 c^*}{\partial y^2} = 0 \qquad (4.26)$$

for the case of a pulse release of radionuclide $\Delta\nu$ at $t = t_e$ or $t^* = 0$. We denote the concentration variable by c^* because it represents only the one-dimensional concentration in the y-direction.

The solution of equation 4.26 is:

$$c^*(y,t^*) = \Delta\nu[4\pi(D_y/k)t^*]^{-1/2} \exp[-\frac{y^2}{4(D_y/k)t^*}]. \qquad (4.27)$$

$\Delta\nu$ must be expressed in Ci/m^2 so that c^* can be expressed in Ci/m^3. We consider that the pulse release $\Delta\nu$ is actually introduced over the short time Δt, and so is introduced over the length Δx, which is the distance the nuclide moves in the time Δt. $\Delta\nu$ is also introduced uniformly throughout the vertical thickness, m, of the aquifer. The total number of curies in the pulse release is equal to $Q'(t)\ \Delta t$, which will be distributed over the horizontal distance of Δx and in the entire thickness of the aquifer. Since equation 4-27 considers only one unit thickness of aquifer, one may write:

$$\Delta\nu = \frac{Q'(t)\ \Delta t}{m\ \Delta x} \qquad (4.28)$$

and

$$c^*(y,t^*) = \frac{Q'(t)\ \Delta t}{m\ \Delta x}\ [4\pi(D_y/k)\ t^*]^{-1/2} \exp[-\frac{y^2}{4D_y/kt^*}] \exp(-\lambda t^*) \qquad (4.29)$$

in which Δx is related to Δt by the velocity of the nuclide, v/k:

$$\Delta x = (v/k)\ \Delta t. \qquad (4.30)$$

Thus we obtain:

$$c^*(y,t^*) = \frac{Q'(t^*)}{mv/k}[4\pi(D_y/k)(t^*)]^{-1/2}\exp[\frac{-y^2}{4(D_y/k)t^*}]\ \exp(-\lambda t^*). \quad (4.31)$$

We now introduce the x-dependence of c^* using the relation of x and t^*. Since the nuclide moves in the aquifer with a velocity v/k for a time t^*, and since we neglect dispersion in the x-direction:

$$x = (v/k)t^* \text{ and,} \quad (4.32)$$

$$t^* = kx/v. \quad (4.33)$$

We substitute equation 4.33 into equation 4.31. We also evaluate $Q'(t)$ at the time "$t - (kx/v)$", since the nuclide entered the aquifer at time "$t - t^*$", which is "$t - (kx/v)$".

We then obtain:

$$c^*(x,y,t) = \frac{Q'(t - kx/v)}{mv/k}[4\pi(D_y/k)(kx/v)]^{-1/2} \cdot \exp(-\frac{y^2v}{4(D_y/k)kx})\ \exp(-\lambda kx/v)$$

which can be simplified to:

$$c^*(x,y,t) = \frac{kQ'(t\ kx/v)}{}(4\pi D_y xv)^{-1/2} \cdot \exp(-\frac{y^2v}{4(D_y/k)kx})\ \exp(-\lambda kx/v). \quad (4.34)$$

The concentration c^* is the total concentration of radionuclide in the aquifer, including both nuclide dissolved in water and nuclide sorbed on rock. To obtain the actual concentration c dissolved in water, we must first multiply c^* by $1/k$, which is the fraction of the nuclide in the water, and then divide by ε, the porosity, to account for the fact that the water occupies only the pores in the aquifer formation. With these changes, we obtain:

$$c(x,y,t) = \frac{Q'(t - kx/v)}{m\varepsilon}[4\pi\ D_y vx]^{-1/2}\exp(-\frac{y^2v}{4D_y x})\ \ \exp(-\lambda kx/v). \quad (4.36)$$

The maximum downstream center-line distance to which a given nuclide can travel is governed by its transit time, kx/v. The concentration of the nuclide at any distance before its transit time being reached should be zero. In order to account for this mathematically, we introduce the unit step function $U(t - t_e - kx/v)$ to equation 4.36, which has the following properties:

$$U(t - t_e - kx/v) = \begin{cases} 0 \text{ for } t - t_e < kx/v \\ 1 \text{ for } t - t_e \geq kx/v. \end{cases} \tag{4.37}$$

If desired, equation 4.36 may be further simplified by introducing the relationship between the transverse dispersion coefficient, D_y, and the interstitial velocity v:

$$D_y = A_t v \tag{4.38}$$

where A_t is the transverse diffusivity, m.

For this generic assessment, we assumed a value of 6 m for A_t. When this relationship is substituted into equation 4.35 and the U-function included, we obtain:

$$c(x,y,t) = \frac{Q'(t - kx/v)}{m\varepsilon v} [4\pi A_t x]^{-1/2} \exp(- \frac{y^2}{4A_t x}) \cdot$$
$$\exp[-\lambda(kx/v)] \;\; U(t-t_e-(kx/v)). \tag{4.39}$$

4.1.3. Concentration in the aquifer due to drilling

There are four different expressions that describe the concentration of a released radionuclide in the aquifer. We derived these by combining the release rates developed in Section 4.1.1 with the aquifer transport equation, equation 4.39.

The appropriate release rate equations are 4.3, 4.9, 4.12, and 4.20. We evaluate each of these equations at the time "t - kx/v", so that we can evaluate the dose at point (x,y) at time t.

Leach-limited release from waste or brine pocket hit

We can transform equation 4.3 by substituting "t - kx/v" for "t":

$$Q'(t - \frac{kx}{v}) = fLQ_o \exp[-\lambda(t - kx/v)] \cdot$$
$$\exp[-L(t-t_e-kx/v)] \tag{4.3a}$$

and combine it with equation 4.39 to give:

$$c(x,y,T) = \frac{fLQ_0}{m\epsilon v} \exp[-\lambda(t-kx/v)] \, [4\pi A_t x]^{-1/2} \exp[-\frac{y^2}{4A_t x}] \cdot$$

$$\exp(-\lambda \frac{kx}{v}) \exp[-L(t-t_e-\frac{kx}{v}) \, U(t-t_e-\frac{kx}{v})]. \qquad (4.40)$$

We can combine the radioactive decay factors to give:

$$c(x,y,t) = \frac{fLQ_0 \, (4\pi A_t x)^{-1/2}}{m\epsilon v} \exp(-\lambda t) \exp[-L \, (t-t_e-\frac{kx}{v})] \cdot$$

$$\exp\,[-\frac{y^2}{4A_t x}] \, U\,(t-t_e-\frac{kx}{v}). \qquad (4.41)$$

Equation 4.41 is appropriate for determining the concentration of nuclides which are not limited by solubility when the drill strikes waste directly or strikes a brine pocket.

Solubility-limited releases

Combining equations 4.4 and 4.5 and evaluating at "t - kx/v", we arrive at:

$$Q'(t - \frac{kx}{v}) = S \; A \; K(t - \frac{kx}{v}) \; i(t - \frac{kx}{v}) \qquad (4.42)$$

with equation 4.39, we obtain:

$$c(x,y,t) = \frac{S \; A \; K(t - kx/v) \; i(t - kx/v)}{m\epsilon v} \, (4\pi A_t x)^{-1/2} \cdot$$

$$\exp(-\frac{y^2}{4A_t x}) \exp(-\lambda kx/v) \; U(t-t-_e(kx/v)). \qquad (4.43)$$

Equation 4.43 is appropriate for determining the concentration of solubility-limited nuclides when the drill strikes waste directly or strikes a brine pocket or repository water.

Uranium oxide-limited releases from waste or brine pocket hit

Situations limited by the solubility of the uranium oxide matrix are similar to leaching. When we combine equation 4.12, evaluated at $t - kx/v$:

$$Q'(t - kx/v) = \frac{s_u\ F(t)}{m_u} Q_o \exp[-\lambda(t - (kx/v))] \qquad (4.12)$$

with equation 4.5 also evaluated at $t - kx/v$:

$$F = A\ K(t - kx/v)\ i(t - kx/v) \qquad (4.5)$$

with equation 4.39, we obtain:

$$c(x,y,t) = \frac{s_u\ A\ K(t - \frac{kx}{v})\ i(t - \frac{kx}{v})}{m_u\ m\varepsilon v} Q_o \exp[-\lambda(t - \frac{kx}{v})][4\pi A_t x]^{-1/2} \cdot$$

$$\exp\left(-\frac{y^2}{4A_t x}\right) \exp(-\lambda kx/v)\ U[t-t_e-(kx/v)]. \qquad (4.44)$$

By combining the decay terms, we obtain:

$$c(x,y,t) = \frac{s_u\ AK(t - \frac{kx}{v})\ i(t - \frac{kx}{v})}{m_u\ m\varepsilon v} Q_o \exp(-\lambda t) \cdot$$

$$(4\pi\ A_t x)^{-1/2} \exp\left(-\frac{y^2}{4\ A_t x}\right) U(t-t_e- \frac{kx}{v}). \qquad (4.45)$$

Equation 4.45 is appropriate for determining the concentration of nuclides when this concentration is limited by the solubility of the uranium oxide matrix, when the drill either strikes waste directly or strikes a brine pocket.

<u>Leach-limited releases from the granite tank</u>

When we combine equation 4.20, evaluated at "$t - kx/v$":

$$Q'(t-kx/v) = F(t-kx/v)\left(\frac{Q_o}{V}\right) \exp[-\lambda(t-kx/v)][1-\exp[(-L)(t - t_c)]] \qquad (4.20)$$

with equation 4.5 and equation 4.39, we obtain:

$$c(x,y,t) = \frac{A\ K(t - \frac{kx}{v})\ i(t - \frac{kx}{v}) Q_o}{m\varepsilon v\ V} \exp[-\lambda(t - \frac{kx}{v})][4\pi A_t x]^{-1/2} \cdot$$

$$[1 - \exp[(-L)(t-t_c- \frac{kx}{v})]] \exp\left[-\frac{y^2}{4A_t x}\right] \cdot$$

$$\exp[-\lambda(kx/v)]\ U(t-t_e- \frac{kx}{v}). \qquad (4.46)$$

In this equation, we can combine the radioactive decay terms, obtaining:

$$c(x,y,t) = \frac{A\ K(t-\frac{kx}{v})\ i(t-\frac{kx}{v})\ Q_o}{m\varepsilon v\ V} \exp(-\lambda t) \cdot$$

$$(4\pi A_t x)^{-1/2}\ [1-\exp[(-L)(t-t_c-\frac{kx}{v})]] \cdot$$

$$\exp(-\frac{y^2}{4A_t x})\quad U(t-t_e-\frac{kx}{v}). \tag{4.47}$$

Equation 4.47 is appropriate for determining the concentration of nuclides that are not limited by solubility, when the drill strikes repository water in granite. When the nuclide concentration is limited by the solubility of uranium oxide, the uranium leaching constant L_u should be substituted for L in equation 4.47.

4.2. Release to the Aquifer due to Faulting

Faulting events differ considerably from resource exploration drilling events. In one faulting scenario we assume a single fault intersects the waste in a straight line in the direction of aquifer flow, rupturing intact canisters. In the other scenario, we assume the canisters have already failed, and activity from many canisters has dissolved into the repository water in the backfill. This activity, which is in a single "tank", is affected by the fault. These scenarios differ in the fraction of the repository affected by the fault.

The faulting event opens a vertical pathway for a groundwater flow to develop that carries radionuclides from the repository to the overlying aquifer. The radionuclides that enter the upper aquifer are then transported horizontally in the aquifer groundwater. As the radionuclides are transported downstream within the region above the repository, they will be joined by radionuclides being discharged into the aquifer further downstream. Therefore, the radionuclide concentration tends to increase with distance downstream, until the radionuclides pass the edge of the repository. We have calculated only the concentration at the center line of the fault, as a function of the distance downstream from the upstream end of the repository.

The faulting event may be mathematically modeled as equivalent to a large number of drilling events. The concentration of radionuclides at any distance "x" downstream in the aquifer from a borehole was derived in Section 4.1.3. We calculate the concentration at any distance "X" downstream from the upstream repository edge by summing the effect of all the upstream releases. To do this, we replace the borehole with an element of length dx and integrate over all appropriate x values.

4.2.1 Leaching governs release

Equation 4.41 gives the concentration at a point x meters downstream in the aquifer from a borehole release point for all values of y and t . We can use this equation for the increment of concentration, dc, at time t at the distance X from the upstream end of the repository due to a release through the infinitesimal length dx at a distance X from the upstream end of the repository. We can do this by substituting $Q_0 dx/L_n$ for Q_0, since that is the fraction of the inventory available to the length dx, and by substituting the distance (X-x) for x. We can also omit the exponential term in y^2 since we are interested only in the centerline dose value (the highest dose). With these changes, we obtain:

$$dc(x,t)_X = \frac{fLQ_0 dx}{m\varepsilon v L_n} \exp(-\lambda t) \, [4\pi A_t (X-x)]^{-1/2} \cdot \exp[-L(t-t_e-\frac{k(X-x)}{v}] \, U[t-t_e-\frac{k(X-x)}{v}] \tag{4.48}$$

where,

$dc(x,t)_X$ is the infinitesimal increment of concentration at X due to the contribution of the release emerging at x meters from the point of interest X,

L_n is the length of the repository,

X is the distance from the upstream end of the repository and, the other symbols are the same as previously defined.

To simplify the process of integration, we now substitute $z = X - x$, and group all terms not involving z, so that equation 4.48 becomes:

$$dc(X-z,t)_X = \frac{fLQ_o}{m\varepsilon vL_n(4\pi A_t)^{1/2}} \exp(-\lambda t) \exp[-L(t - t_e)] \cdot$$
$$z^{-1/2} \exp[-L \frac{kz}{v}] \; U \; (t-t_e- \frac{kz}{v})(-dz). \quad (4.49)$$

To obtain the concentration of a radionuclide at X and at a time T, the time elapsed from the occurrence of the event of interest, we integrate equation 4.49:

$$c(X,T) = \int_X^0 dc(X-z,T). \quad (4.50)$$

We can eliminate the U factor by noting that $U = 0$ when $z > (v/k)(T-t_e)$ and adjusting the limits accordingly. We also reverse the limits to remove the minus sign from dz. Equation 4.50 then becomes:

$$c(X,T) = \gamma \int_0^{(v/k)(t-t_e)} [z^{-1/2} \exp(- \frac{Lkz}{v})]dz \quad (4.51)$$

where T is expressed in $t - t_e$ and,

γ is the part of the expression independent of z:

$$\gamma = \frac{fLQ_o \exp(-\lambda t) \exp[-L(t - t_e)]}{m\varepsilon vL_n(4\pi A_t)^{1/2}} \cdot$$

The integral in equation 4.51 cannot be expressed analytically, but we evaluated it numerically by Simpson's rule. The numerical analysis is complicated by the fact that the integrand becomes infinite for $z = 0$. Physically, this is because the diluting flow in the aquifer is one-dimensional, with no transverse dimension, and so is equal to zero. Since any well would have a finite size, and would draw from a rather large area, it is reasonable to exclude a one-meter distance, so that the concentration, with the new limits on the integral, becomes:

$$c(X,T) = \gamma \int_1^{(v/k)(t-t_e)} [z^{-1/2} \exp(- \frac{Lkz}{v})] \; dz. \quad (4.52)$$

When the upper limit is larger than the length of the repository, it is replaced by L_n.

4.2.2 Radionuclide solubility governs release

The calculation of c(X,T) is done in a manner similar to that used in section 4.2.1, beginning with the appropriate equation, equation 4.43. In this way, we obtain an equation analagous to equation 4.48:

$$dc(x,t)_X = \frac{fSAK[t-k(X-x)/v]\ i[t-k(X-x/v)]dx}{L_n m\varepsilon v}\,[4\pi A_t(X-x)]^{-1/2}\ \cdot$$

$$\exp[-\lambda k(X-x)/v]\ U[t-t_e-(k(X-x)/v)]. \qquad (4.53)$$

This expression may be evaluated by the technique used in the previous section. One additional simplification is possible--in the calculations done for this report, a constant permeability was used, so that K' = 0. The K for faulting is the permeability produced by the fault. This premeability may be expected to decrease with time by compaction and filling of the fault zone. Constant permeability is, therefore, conservative.

In this case, as before, we are interested only in the annual dose rates on the center line, so we may omit the exponential term in y^2. We substitute z = X - x, and integrate from 0 to X. Before evaluating the integral, we change the limits on the integral as in section 4.2.1. The concentration of the radionuclide at X = 4,000 m, corresponding to the downstream end of the repository, at time T (= t - t_e) is then:

$$c(X,T) = \frac{fSAK}{L_n\ m\varepsilon v(4\pi A_t)^{1/2}} \int_1^{(v/k)(t-t_e)} z^{-1/2}\ i(t-\frac{kz}{v})\ \exp(-\frac{\lambda kz}{v})\ dz. \qquad (4.54)$$

The terms in this equation are defined in Sections 4.1.1., 4.1.2, and 4.2.1.

4.2.3. Uranium oxide solubility governs release

The form of the equation in this case is identical to that for the leaching-governed case (Section 4.2.1), except that L is replaced by

L_u (equation 4.10) for those nuclides which are retained the UO_2 matrix. Because of this similarity, the equation is not repeated here.

4.2.4 Fault disturbs the granite tank

The equation for the aquifer concentration resulting from a drill striking repository water was given in equation 4.47. In developing equation 4.20, for entry of nuclides into the aquifer when a drill strikes repository water, we considered that removal of radioactive material from the repository water by the borehole flow to the aquifer was negligible (see section 4.1.1.3.1). Since faulting causes a much larger flow of water through the repository to the aquifer, this approximation is not appropriate here. We included the factor F/V (see equation 4.13) in the computer program for calculating doses from connecting the repository water to the aquifer through a fault. The concentration at $X = 4{,}000$ m at time t is calculated by the same transformation and integration used in sections 4.2.1, 4.2.2, and 4.2.3.

4.3. Release to the Land Surface

Nuclides may be released to the land surface as a result of drilling for resources. This is a point release, limited to the drilling site. Nuclides released to the land surface can affect individuals who breathe air contaminated by resuspended radioactive particles and who stand on contaminated ground.

We considered two modes of release of waste material to the land surface. One is a direct hit on waste by a drill. The other assumes that a waste canister has failed and that the drill then penetrates into a surrounding brine pocket (in a salt repository) or tank (in granite) contaminated by waste.

After the radionuclides reach the surface, the mathematical description of their dispersion and of the surface contamination are the same for both models. The release that occurs via an intermediate stage (e.g., a brine pocket) is more complicated because it includes transport of nuclides from a failed waste canister to the brine pocket or tank.

Radionuclides deposited on land surface are resuspended into the air, moved by air currents, and redeposited on the ground. The radionuclides are diluted as they move in the air and are depleted by deposition on the ground. Estimation of dose from inhalation requires knowledge of the air concentration. Nelson, et al. (Ne 78), give equations for the calculation of the air concentration as a function of time and distance from a point source. This air concentration decreases with time due to depletion by radioactive decay and deposition, and removal to the soil sink. The DECF's (Ki 76, Du 79) give the fiftieth year dose equivalent corresponding to a constant rate of intake over the 50-year period.

We used the primary air concentration X_o^d, neglecting secondary resuspension, as an approximation to the total air concentration. Using X_o^d facilitates the calculation because the time component is separable in the function. In Table 4.1., Nelson et al. (Ne 78) give values of primary (X_o^d) and secondary (X_1^d) air concentrations at one kilometer from a ground surface point source of plutonium-239. These values show that the secondary concentration is only two percent of the primary air concentrations fifty years after contamination occurred and much less before that.

The equation for the air concentration due to direct (first-pass) dispersion from the source is (Ne 78):

$$X_o^d(r,t) = Q\lambda_r(X/Q')(r/r_n)^{-\sigma} \exp[-(\frac{r}{r_d})^{2-\sigma}] \exp[-\lambda_t(t - t_e)] \quad (4.55)$$

where X_o^d is the air concentration of a radionuclide at a distance r from the source and at time t (after the initiating event at t_e), taking into account depletion of the plume. The subscript "o" denotes the air concentration due to primary (first pass) dispersion of contaminated material from the point source,

Q is the amount of radionuclide released to the ground surface (Ci),

(X/Q') is the atmospheric dilution factor at distance r (yr/m^3),

r_n is a reference distance (m),

σ is the slope of log (X/Q') vs log r, determined empirically,

r_d is the characteristic depletion distance,

λ_t is the total removal rate = $\lambda_r + \lambda_s + \lambda$ (yr^{-1}),

λ_r = resuspension rate (yr^{-1}),
λ_s = rate of depletion into the soil (yr^{-1}) and,
λ = radionuclide decay rate (yr^{-1}).

X_o^d is separable into functions of r and t:

$$X_o^d\ (r,t) = Q\ M\ N(r)\ S(t) \tag{4.56}$$

where $M = \lambda_r\ (X/Q')$ (4.56a)
$N = (r/r_n)^{-\sigma} \exp[-(r/r_d)^{2-\sigma}]$ and, (4.56b)
$S = \exp[-\lambda_t(t_e)]$. (4.56c)

Separability of $X_o^d(r,t_e)$ makes it easy to treat nuclides other than Pu-239, since equations for their air concentrations will differ only in the value of λ_t. Separability also makes it easy to calculate the air concentration at different distances. Parameters for radionuclide transport were taken from Nelson et al. (Ne 78). A low resuspension rate ($\lambda_r = 3.15 \times 10^{-4}\ yr^{-1}$) was selected as appropriate for the borehole material brought to the surface, which would be wet, and in a low dusting form. Furthermore, much of the radioactive material would probably be covered by inert rock fragments and drilling mud.

M N(r) can be evaluated for all nuclides at r = 1 km, using Nelson's plutonium values of 1.01E-9 per second (= 3.19E-2 yr^{-1}) for λ_t, 1.8E-17 Q Ci/m^3 for X_o^d at 1 km and 1 year and,

$$S(t_e = 1) = \exp(-3.19E-2) = 0.969, \tag{4.57}$$

$$M\ N(r = 1\ km) = \frac{1.8E-17}{0.969} = 1.86E-17\ m^{-3}. \tag{4.58}$$

The integrated atmospheric concentration, E_b (Ci-yr/m^3), around an individual at a distance "r" over a 50-year time period can be obtained by integration:

$$E_b(r,t) = \int_0^{50} X_o^d(r,t_e)\ dt \tag{4.59}$$

$$= QMN \int_0^{50} \exp(-\lambda_t t_e)\ dt \tag{4.59a}$$

$$= \frac{QMN}{\lambda_t}\ [1 - \exp(-50\lambda_t)]. \tag{4.59b}$$

Table 4.1

Primary and Secondary Air Concentrations

$t-t_e$ (yr)	χ_o^d (Ci/m^3)	χ_1^d (Ci/m^3)
0.01	1.9E-17	6.0E-23
0.1	1.9E-17	6.0E-22
1	1.8E-17	5.8E-21
10	1.4E-17	4.4E-20
25	8.6E-18	6.7E-20
50	3.9E-18	6.1E-20

The average air concentration is obtained by dividing this equation by 50 years:

$$(\chi_o^d)_{av}(r,t) = \frac{QMN}{50\lambda_t}[1 - \exp(-50\lambda_t)]. \tag{4.60}$$

The dose equivalent rate after breathing air contaminated to this average level for 50 years, is:

$$H'_{bik} = \frac{QMNU_bD_{bik}}{50\lambda_t}[1 - \exp(-50\lambda_t)] \tag{4.61}$$

where b refers to breathing, i to nuclide i, and k to organ k. There is an equation of this type for each nuclide and each organ.

4.3.1 Direct drilling hit on waste

In this scenario, we consider that the drill strikes solid waste, either in a canister prior to the canister failure time, or exposed after that time. In either event, we assume the drill removes 15 percent of the waste in one canister to the surface (ADL 79). Equation 4.1 gives the total inventory of the nuclide in the repository at the event time t_e. The quantity, Q, removed to the surface is:

$$Q(t_e) = 0.15\ fQ_o \exp(-\lambda t_e). \tag{4.62}$$

Equation 4.62 may be substituted into equation 4.61 to obtain the 50th-year dose rate.

If the drilling event occurs after canister failure, the inventory of nuclides in the waste would be further reduced by depletion through leaching by the factor "$\exp[-L(t_e - t_c)]$". We did not include this factor, so that our calculations are conservative to this extent.

4.3.2 Liquid from a brine pocket or granite tank

Leaching governs release

In these scenarios, we assume the waste is completely contained in its canister until the failure time, which we assume is 100 years in salt or 500 years in granite (ADL 79). The wastes then begin to leach and dissolve into the repository liquid. In a salt repository, the contents of two failed canisters leach into a common volume which we have termed a "brine pocket." In granite, all the failed canisters leach into one common volume, or "tank." When a well is drilled into a brine pocket, the lithostatic pressure results in a rapid release of the entire contents to the surface. We simplified the model by assuming that the release was instantaneous. The consequences of the release depend on the time at which the hole is drilled and the volume of the brine pocket. There are, of course, no radiological consequences if the hole is drilled prior to canister failure.

We have already discussed the accumulation of radionuclides in granite repository water in section 4.1.1. The differential equations 4.13 and 4.14 describe this movement. There is no flow through the repository before the drilling event releases radionuclides to the surface, so the (F/V) term in equation 4.13 can be set equal to zero. Equation 4.18 then gives the quantity of a nuclide leached into solution in the repository water. We modify equation 4.18 slightly by dividing by V, the volume of the brine pocket or granite tank, in order to convert quantity to concentration. We also introduce the factor f to denote the fraction of the repository exposed to the brine pocket or tank. This gives, for the concentration at the event time t_e:

$$c(t_e) = \frac{fQ_o \exp(-\lambda t_e)}{V} (1 - \exp[(-L)(t_e - t_c)]). \tag{4.63}$$

The fraction f is 1 in granite, since all the waste is exposed to repository water. In salt, it corresponds to two canisters (ADL 79), and therefore equals 2/35,000. The liquid volume V is 2,000,000 m^3 in granite and 0.06 m^3 in salt.

We assume a volume of 200 m^3 (ADL 79) is released to the surface from drilling in granite, while the entire contents of the brine pocket are released to the surface from drilling in salt. The total amounts, Q, released to the surface then become:

$$Q = \frac{200Q_o \exp(-\lambda t_e)}{2,000,000} [1 - \exp(-L)(t_e - t_c)] \tag{4.64}$$

in granite, and in salt:

$$Q = fQ_o \exp(-\lambda t_e) [1 - \exp[(-L)(t_e - t_c)]. \tag{4.65}$$

Nuclide solubility governs release

For nuclides whose entry into the repository liquid is limited by solubility, the concentration in the brine or water is simply equal to the solubility S (Ci/m^3). The amount delivered to the surface is then simply:

$$Q = 200\ S \tag{4.66}$$

in granite, and

$$Q = 0.06\ S \tag{4.67}$$

in salt.

Chapter 5

Results of the Reference Disposal System Analysis

This chapter presents the annual dose rate and contaminated area results from our reference disposal system. The calculations were done using an EPA computer code (Se 81) that numerically models the release of radionuclides from the repository (the source term) and their environmental transport. The code calculates the annual dose rate for each nuclide at preselected dose times and distances, and then sums over all the nuclides to yield the total annual dose rate for that release. The code also calculates areas contaminated above preselected dose rate limits. The area tables are useful indicators of the potential health risk from the repository because the probability that someone will incur the indicated dose is proportional to the contaminated area. We considered four event times: 200, 1000, 3350 and 7500 years, and used the 1000-year event as the reference time. The reference data on the important nuclides appear in Table 5.1. The code calculates one of two source terms, either leaching- or solubility-limited, as appropriate. A summary table of the maximum annual dose rates is presented in Table 5.43 at the end of this chapter.

The annual dose rate results are in the form of a computer output that gives annual dose rates at 10 preselected distances and 13 preselected times. Table 5.2 is a sample computer output for one release. It gives the annual inhalation dose rate from release to the land surface following drilling that hits the waste 1000 years after repository sealing. It consists of a 13 by 10 table of annual dose rates. The dose times appear on the left side of Table 5.2 and cover 10 years to 10,000 years after the event. The distances are listed at the top of the table and cover 20 meters to 4000 meters. Each location in the table contains three items: the dose rate in rem/yr, the radionuclide that is the largest contributor to the dose and its

Table 5.1

Repository System Characteristics

Parameter Name	Parameter Symbol	Reference Value	Low Value	High Value
Leach rate (yr^{-1})	L	10^{-4}	10^{-5}	10^{-2}
Groundwater velocity (m/yr)	v	2.1	0.21	21

Nuclide	Retardation Factors (k) Reference Value	High Value	Low Value	Solubility (Ci/m^3)
C-14	1	10	1	*
Sr-90	1	100	1	*
Zr-93	100	10,000	1	2E-6
Tc-99	1	1	1	2E-5
Sn-126	10	1,100	1	0.03
I-129	1	1	1	*
Cs-135	1	1,000	1	*
Cs-137	1	1,000	1	*
Np-237	100	100	1	7.2E-7
Pu-242	100	10,000	1	4E-6
Pu-240	100	10,000	1	2.2E-4
Pu-239	100	10,000	1	6E-5
Pu-238	100	10,000	1	**
Am-241	100	10,000	1	160.0
Am-243	100	10,000	1	10.0

*Solubility so high that nuclide was leach-limited in all cases.

**Pu-238 was considered to be leach-limited in all cases, even though its solubility may be limiting in a few cases. This approximation is conservative.

percent of the total dose rate. In Table 5.2, for example, the output for a dose time of 10 years and a distance of 50 meters is:

2.96E+00
AM-241
54.2%

which indicates an annual dose rate of 2.96 rem/yr, 54.2% of which is from Am-241, the largest contributor.

Table 5.3 shows areas of the land surface contaminated above preselected dose rates for this release. Dose times are listed in the left column. The five columns of data following the dose times are cumulative areas in hectares (ha = 10^4 m^2) contaminated above preselected values. The area tables are given for drilling releases only.

5.1 Release to the Aquifer Due to Drilling

Tables 5.4, 5.5 and 5.6 demonstrate the relative movement in groundwater of nuclides with different retardation factors. These tables are the results of three special computer model runs, one for technitium-99 (Tc-99) only, another for tin-126 (Sn-126) only, and the last for Am-243 only. The rate at which each radionuclide moves in the groundwater is equal to v/k; Tc-99 flows at 2.1 m/yr, Sn-126 at 0.21 m/yr and Am-243 at 0.021 m/yr. These are average values reflecting the fraction of time that the nuclide is immobile or is flowing with the aquifer. When more than one nuclide is present, each will travel at its own rate depending upon its retardation factor, K, which may have a value of 1, 10, or 100 depending on the particular nuclide. The numerical values in Tables 5.4, 5.5, and 5.6 are dose rates that would result from drinking groundwater. Since the special runs, with only one nuclide present in each, represent an artificial situation, the values should be used only for relative purposes within one table.

Table 5.4 shows that the rapidly moving Tc-99 travels 20 meters within ten years, 1000 meters within 500 years, and 4000 meters within 2000 years. Values at any distance decrease very slowly over time;

Table 5.2

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Hits Waste

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.12E+01 AM-241 54.2%	2.96E+00 AM-241 54.2%	1.07E+00 AM-241 54.2%	3.83E-01 AM-241 54.2%	9.59E-02 AM-241 54.2%	5.12E-02 AM-241 54.2%	3.25E-02 AM-241 54.2%	1.70E-02 AM-241 54.2%	1.06E-02 AM-241 54.2%	3.22E-03 AM-241 54.2%
2.00E+01	1.10E+01 AM-241 53.9%	2.92E+00 AM-241 53.9%	1.06E+00 AM-241 53.9%	3.78E-01 AM-241 53.9%	9.46E-02 AM-241 53.9%	5.05E-02 AM-241 53.9%	3.21E-02 AM-241 53.9%	1.67E-02 AM-241 53.9%	1.04E-02 AM-241 53.9%	3.17E-03 AM-241 53.9%
5.00E+01	1.06E+01 AM-241 52.8%	2.80E+00 AM-241 52.8%	1.01E+00 AM-241 52.8%	3.63E-01 AM-241 52.8%	9.08E-02 AM-241 52.8%	4.85E-02 AM-241 52.8%	3.08E-02 AM-241 52.8%	1.61E-02 AM-241 52.8%	1.00E-02 AM-241 52.8%	3.05E-03 AM-241 52.8%
1.00E+02	9.91E+00 AM-241 51.0%	2.62E+00 AM-241 51.0%	9.49E-01 AM-241 51.0%	3.40E-01 AM-241 51.0%	8.50E-02 AM-241 51.0%	4.54E-02 AM-241 51.0%	2.88E-02 AM-241 51.0%	1.50E-02 AM-241 51.0%	9.36E-03 AM-241 51.0%	2.85E-03 AM-241 51.0%
2.00E+02	8.71E+00 AM-241 47.4%	2.30E+00 AM-241 47.4%	8.34E-01 AM-241 47.4%	2.99E-01 AM-241 47.4%	7.47E-02 AM-241 47.4%	3.99E-02 AM-241 47.4%	2.53E-02 AM-241 47.4%	1.32E-02 AM-241 47.4%	8.23E-03 AM-241 47.4%	2.51E-03 AM-241 47.4%
5.00E+02	6.11E+00 AM-241 36.9%	1.61E+00 AM-241 36.9%	5.85E-01 AM-241 36.9%	2.09E-01 AM-241 36.9%	5.24E-02 AM-241 36.9%	2.79E-02 AM-241 36.9%	1.78E-02 AM-241 36.9%	9.26E-03 AM-241 36.9%	5.77E-03 AM-241 36.9%	1.76E-03 AM-241 36.9%
1.00E+03	3.71E+00 PU-240 42.7%	9.81E-01 PU-240 42.7%	3.55E-01 PU-240 42.7%	1.27E-01 PU-240 42.7%	3.18E-02 PU-240 42.7%	1.70E-02 PU-240 42.7%	1.08E-02 PU-240 42.7%	5.63E-03 PU-240 42.7%	3.50E-03 PU-240 42.7%	1.07E-03 PU-240 42.7%
2.00E+03	1.73E+00 PU-240 49.8%	4.58E-01 PU-240 49.8%	1.66E-01 PU-240 49.8%	5.95E-02 PU-240 49.8%	1.49E-02 PU-240 49.8%	7.94E-03 PU-240 49.8%	5.05E-03 PU-240 49.8%	2.63E-03 PU-240 49.8%	1.64E-03 PU-240 49.8%	4.99E-04 PU-240 49.8%
5.00E+03	2.92E-01 PU-239 50.0%	7.73E-02 PU-239 50.0%	2.80E-02 PU-239 50.0%	1.00E-02 PU-239 50.0%	2.51E-03 PU-239 50.0%	1.34E-03 PU-239 50.0%	8.50E-04 PU-239 50.0%	4.43E-04 PU-239 50.0%	2.76E-04 PU-239 50.0%	8.40E-05 PU-239 50.0%
1.00E+04	1.72E-02 PU-239 59.0%	4.54E-03 PU-239 59.0%	1.64E-03 PU-239 59.0%	5.88E-04 PU-239 59.0%	1.47E-04 PU-239 59.0%	7.85E-05 PU-239 59.0%	4.99E-05 PU-239 59.0%	2.60E-05 PU-239 59.0%	1.62E-05 PU-239 59.0%	4.93E-06 PU-239 59.0%

Table 5.3

Area (ha*) of the Land Surface Contaminated Above the Specified Dose Rate Levels Following a Direct Drilling Hit on Waste 1000 Years after Sealing

Time After Drilling (yr)	Dose Levels (rem/yr)		
	0.5	5.0	50
10	10.5	0.57	0
20	10.4	0.56	0
50	10.1	0.54	0
100	9.5	0.51	0
200	8.3	0.44	0
500	4.8	0.24	0
1000	2.5	0	0
2000	0.8	0	0
5000-10,000	0	0	0

*1 ha = 10^4 square meters

Table 5.4

Example of Dispersion in Groundwater of a Nuclide with a Retardation Factor of One
(All Dose Rate Values are Relative)

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	6.70E-06 TC -99 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	6.68E-06 TC -99 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	6.61E-06 TC -99 100.0%	4.20E-06 TC -99 100.0%	2.99E-06 TC -99 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	6.51E-06 TC -99 100.0%	4.14E-06 TC -99 100.0%	2.95E-06 TC -99 100.0%	2.11E-06 TC -99 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	6.32E-06 TC -99 100.0%	4.02E-06 TC -99 100.0%	2.86E-06 TC -99 100.0%	2.05E-06 TC -99 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	5.87E-06 TC -99 100.0%	3.72E-06 TC -99 100.0%	2.65E-06 TC -99 100.0%	1.89E-06 TC -99 100.0%	1.24E-06 TC -99 100.0%	1.05E-06 TC -99 100.0%	9.39E-07 TC -99 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	5.34E-06 TC -99 100.0%	3.38E-06 TC -99 100.0%	2.40E-06 TC -99 100.0%	1.71E-06 TC -99 100.0%	1.11E-06 TC -99 100.0%	9.26E-07 TC -99 100.0%	8.22E-07 TC -99 100.0%	7.10E-07 TC -99 100.0%	6.58E-07 TC -99 100.0%	0.0 NONE 0.0%
2.00E+03	4.70E-06 TC -99 100.0%	2.98E-06 TC -99 100.0%	2.11E-06 TC -99 100.0%	1.50E-06 TC -99 100.0%	9.62E-07 TC -99 100.0%	7.96E-07 TC -99 100.0%	6.99E-07 TC -99 100.0%	5.88E-07 TC -99 100.0%	5.27E-07 TC -99 100.0%	4.57E-07 TC -99 100.0%
5.00E+03	3.85E-06 TC -99 100.0%	2.43E-06 TC -99 100.0%	1.72E-06 TC -99 100.0%	1.22E-06 TC -99 100.0%	7.77E-07 TC -99 100.0%	6.37E-07 TC -99 100.0%	5.55E-07 TC -99 100.0%	4.58E-07 TC -99 100.0%	4.02E-07 TC -99 100.0%	3.01E-07 TC -99 100.0%
1.00E+04	3.43E-06 TC -99 100.0%	2.17E-06 TC -99 100.0%	1.53E-06 TC -99 100.0%	1.08E-06 TC -99 100.0%	6.86E-07 TC -99 100.0%	5.61E-07 TC -99 100.0%	4.86E-07 TC -99 100.0%	3.98E-07 TC -99 100.0%	3.45E-07 TC -99 100.0%	2.47E-07 TC -99 100.0%

Table 5.5

Example of Dispersion in Groundwater of a Nuclide with a Retardation Factor of Ten
(All Dose Rate Values are Relative)

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.23E-02 SN-126 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.21E-02 SN-126 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.14E-02 SN-126 100.0%	1.37E-02 SN-126 100.0%	9.93E-03 SN-126 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	2.03E-02 SN-126 100.0%	1.30E-02 SN-126 100.0%	9.41E-03 SN-126 100.0%	6.98E-03 SN-126 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+03	1.82E-02 SN-126 100.0%	1.17E-02 SN-126 100.0%	8.46E-03 SN-126 100.0%	6.27E-03 SN-126 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+03	1.32E-02 SN-126 100.0%	8.47E-03 SN-126 100.0%	6.13E-03 SN-126 100.0%	4.55E-03 SN-126 100.0%	3.32E-03 SN-126 100.0%	3.05E-03 SN-126 100.0%	2.98E-03 SN-126 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+04	7.74E-03 SN-126 100.0%	4.96E-03 SN-126 100.0%	3.59E-03 SN-126 100.0%	2.67E-03 SN-126 100.0%	1.94E-03 SN-126 100.0%	1.79E-03 SN-126 100.0%	1.74E-03 SN-126 100.0%	1.81E-03 SN-126 100.0%	1.99E-03 SN-126 100.0%	0.0 NONE 0.0%

Table 5.6

Example of Dispersion in Groundwater of a Nuclide with a Retardation Factor of One Hundred
(All Dose Rate Values are Relative)

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	4.28E+01 AM-243 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+03	3.54E+01 AM-243 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+03	2.00E+01 AM-243 100.0%	1.46E+01 AM-243 100.0%	1.31E+01 AM-243 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+04	7.70E+00 AM-243 100.0%	5.62E+00 AM-243 100.0%	5.04E+00 AM-243 100.0%	5.74E+00 AM-243 100.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%

values at any time decrease fairly slowly with increasing distance. By several hundred years after drilling, the Tc-99 has spread extensively. Table 5.6 shows that the slowly moving nuclide Am-243 is much more restricted. It does not appear in the table for the first 1000 years, since it takes this long to travel 20 meters; even at 10,000 years, it has not yet traveled 500 meters. The americium table is characterized by the large number of zero dose rate values, in contrast to the technetium table. The movement of Sn-126, given in Table 5.5, is intermediate betweeen those of technetium and americium.

5.1.1 Direct hit on waste

Table 5.7 gives the results of our base case for a direct hit drilling release to an aquifer. The event has occurred 1000 years after the repository is sealed. The shorter-lived nuclides, Sr-90 and Cs-137, have decayed. Cesium (Cs), iodine (I) and technetium, each with a retardation factor of 1, move 21 meters in 10 years, and therefore give the dose rate at location (20 m, 10 yr) in the table. At the 100-year dose time Sn-126, with a retardation factor of 10, has moved 21 meters and contributes most of the (20 m, 100 yr) dose rate. The nuclides with a retardation factor of 1 have moved farther, giving doses at distances up to 200 meters. At 1000 years after the event, all nuclides have contaminated parts of the aquifer. Dose rates increase markedly at 1000 years because of the arrival of Am-241, with a large inventory and a large DECF. Am-241 is dominant at short distances for about 3000 years after the event, then Am-243 becomes the major contributor. The half-life of Am-243 is longer, hence it does not decay as quickly.

The 10,000-year dose time exhibits an interesting effect. Between 100 and 200 meters, the dose rate rises with distance. This is because the material at 200 meters was leached out of the canister 500 years earlier when the inventory was higher. The material at 200 meters has traveled 9500 years in the aquifer to reach that point. It left the repository about 500 years after sealing. The material at 100 meters

Table 5.7

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Hits Waste

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.96E-03 CS-135 58.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.96E-03 CS-135 58.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.95E-03 CS-135 58.6%	1.24E-03 CS-135 58.6%	8.77E-04 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.42E-02 SN-126 92.0%	1.23E-03 CS-135 58.7%	8.70E-04 CS-135 58.7%	6.18E-04 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.40E-02 SN-126 92.0%	1.21E-03 CS-135 59.0%	8.57E-04 CS-135 59.0%	6.09E-04 CS-135 59.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.32E-02 SN-126 92.1%	1.49E-02 SN-126 92.2%	1.07E-02 SN-126 92.4%	5.82E-04 CS-135 59.9%	3.74E-04 CS-135 59.9%	3.09E-04 CS-135 59.9%	2.71E-04 CS-135 59.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	6.25E+02 AM-241 93.1%	1.41E-02 SN-126 92.4%	1.02E-02 SN-126 92.5%	7.52E-03 SN-126 92.8%	3.47E-04 CS-135 61.3%	2.87E-04 CS-135 61.3%	2.52E-04 CS-135 61.3%	2.10E-04 CS-135 61.3%	1.87E-04 CS-135 61.3%	0.0 NONE 0.0%
2.00E+03	1.51E+02 AM-241 76.6%	1.26E-02 SN-126 92.6%	9.11E-03 SN-126 92.8%	6.74E-03 SN-126 93.0%	3.01E-04 CS-135 64.0%	2.48E-04 CS-135 64.0%	2.18E-04 CS-135 64.0%	1.82E-04 CS-135 64.0%	1.62E-04 CS-135 64.0%	1.26E-04 CS-135 64.0%
5.00E+03	2.09E+01 AM-243 95.4%	1.53E+01 AM-243 95.4%	1.37E+01 AM-243 95.4%	4.86E-03 SN-126 93.6%	3.52E-03 SN-126 94.3%	3.22E-03 SN-126 94.9%	3.12E-03 SN-126 95.4%	1.21E-04 CS-135 71.6%	1.07E-04 CS-135 71.6%	8.32E-05 CS-135 71.6%
1.00E+04	7.74E+00 AM-243 99.5%	5.64E+00 AM-243 99.6%	5.06E+00 AM-243 99.7%	5.75E+00 AM-243 99.8%	2.05E-03 SN-126 94.8%	1.88E-03 SN-126 95.3%	1.82E-03 SN-126 95.8%	1.87E-03 SN-126 96.6%	2.04E-03 SN-126 97.2%	4.43E-05 CS-135 81.4%

has taken about 4750 years to reach that point; it left the repository about 5250 years after sealing. During the additional 4750 years that the 100-meter material stayed in the repository, it was subject to leaching that reduced its inventory by about 35%. The concentration of nuclide at 200 meters was reduced by about 30% by diffusive dilution in the aquifer while the nuclide traveled from 100 to 200 meters, not quite enough to make up for the 35% higher concentration at which it left the repository. This is shown mathematically in equation 4.3a, where the last factor is:

$$\exp[(-L)(t-t_e-kx/v)].$$

Rearranged, this factor becomes:

$$\exp(-Lt)\ \exp(Lt_e)\ \exp(+Lkx/v).$$

The last exponential increases as the distance, x, increases. This effect can be seen in many locations of Table 5.7 in the later dose times. This increasing exponential is competing with the diffusion term, which decreases as the square root of distance. The "x" terms are:

$$\frac{\exp(Lkx/v)}{x^{1/2}}\ .$$

Table 5.8 shows the results of the direct hit drilling event occurring 200 years after the repository is sealed. Sr-90 dominates for the first 200 years. At 1000 years, dose rates increase markedly as Am-241 reaches the 20-meter distance. The maximum dose in this case is 2000 rem/yr which occurs at 20 meters and 1000 years; Am-241 contributes 1950 rem/yr. The dose rate from Am-241 in Table 5.7 was 582 rem/yr. The lower value for the 1000-year event is due to additional radiological decay before the drilling intrusion.

The next two tables, 5.9 and 5.10, show the annual dose rates from drilling releases 3350 and 7500 years after sealing. Dose rates are lower than at 1000 years due to radiological decay of the nuclides. Table 5.9 shows a maximum dose rate of 51 rem/yr, 1000 years after the drilling, mostly from Am-243. The amount of Am-241, in the 4350 years

Table 5.8

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
200 Years After Repository Sealing

Drill Hits Waste

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.01E+02 SR -90 76.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	7.92E+01 SR -90 76.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	3.86E+01 SR -90 76.0%	2.45E+01 SR -90 76.0%	1.73E+01 SR -90 76.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.17E+01 SR -90 75.0%	7.40E+00 SR -90 75.1%	5.24E+00 SR -90 75.1%	3.73E+00 SR -90 75.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.09E+00 SR -90 71.7%	6.78E-01 SR -90 73.2%	4.81E-01 SR -90 73.2%	3.41E-01 SR -90 73.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.42E-02 SN-126 88.7%	1.55E-02 SN-126 88.9%	1.12E-02 SN-126 89.1%	8.70E-04 CS-135 40.1%	5.58E-04 CS-135 40.1%	4.61E-04 CS-135 40.1%	4.04E-04 CS-135 40.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	2.00E+03 AM-241 97.7%	1.42E-02 SN-126 92.1%	1.03E-02 SN-126 92.3%	7.58E-03 SN-126 92.6%	3.61E-04 CS-135 59.0%	2.98E-04 CS-135 59.0%	2.61E-04 CS-135 59.0%	2.19E-04 CS-135 59.0%	1.94E-04 CS-135 58.9%	0.0 NONE 0.0%
2.00E+03	4.27E+02 AM-241 91.1%	1.27E-02 SN-126 92.4%	9.19E-03 SN-126 92.6%	6.79E-03 SN-126 92.9%	3.11E-04 CS-135 61.8%	2.57E-04 CS-135 61.8%	2.26E-04 CS-135 61.8%	1.89E-04 CS-135 61.8%	1.67E-04 CS-135 61.8%	1.30E-04 CS-135 61.7%
5.00E+03	2.46E+01 AM-243 87.3%	1.79E+01 AM-243 87.3%	1.61E+01 AM-243 87.3%	4.89E-03 SN-126 93.5%	3.54E-03 SN-126 94.2%	3.24E-03 SN-126 94.8%	3.14E-03 SN-126 95.3%	1.24E-04 CS-135 69.6%	1.10E-04 CS-135 69.6%	8.55E-05 CS-135 69.7%
1.00E+04	8.32E+00 AM-243 99.5%	6.07E+00 AM-243 99.6%	5.44E+00 AM-243 99.7%	6.19E+00 AM-243 99.8%	2.06E-03 SN-126 94.8%	1.89E-03 SN-126 95.3%	1.83E-03 SN-126 95.7%	1.88E-03 SN-126 96.5%	2.06E-03 SN-126 97.2%	4.51E-05 CS-135 80.1%

Table 5.9

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides Released by Borehole Drilling
3350 Years After Repository Sealing

Drill Hits Waste

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.77E-03 CS-135 65.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.76E-03 CS-135 65.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.76E-03 CS-135 65.1%	1.11E-03 CS-135 65.1%	7.88E-04 CS-135 65.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.37E-02 SN-126 92.6%	1.10E-03 CS-135 65.3%	7.83E-04 CS-135 65.3%	5.56E-04 CS-135 65.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.34E-02 SN-126 92.7%	1.09E-03 CS-135 65.5%	7.72E-04 CS-135 65.5%	5.48E-04 CS-135 65.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.27E-02 SN-126 92.7%	1.45E-02 SN-126 92.8%	1.05E-02 SN-126 93.0%	5.26E-04 CS-135 66.3%	3.37E-04 CS-135 66.3%	2.79E-04 CS-135 66.3%	2.44E-04 CS-135 66.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	5.13E+01 AM-243 67.5%	1.38E-02 SN-126 92.9%	9.95E-03 SN-126 93.1%	7.36E-03 SN-126 93.3%	3.15E-04 CS-135 67.6%	2.60E-04 CS-135 67.6%	2.28E-04 CS-135 67.6%	1.91E-04 CS-135 67.6%	1.69E-04 CS-135 67.6%	0.0 NONE 0.0%
2.00E+03	3.20E+01 AM-243 89.5%	1.23E-02 SN-126 93.1%	8.92E-03 SN-126 93.2%	6.60E-03 SN-126 93.5%	2.75E-04 CS-135 70.1%	2.27E-04 CS-135 70.1%	1.99E-04 CS-135 70.1%	1.66E-04 CS-135 70.1%	1.47E-04 CS-135 70.1%	1.15E-04 CS-135 70.1%
5.00E+03	1.62E+01 AM-243 99.6%	1.18E+01 AM-243 99.6%	1.06E+01 AM-243 99.7%	4.77E-03 SN-126 93.9%	3.45E-03 SN-126 94.6%	3.16E-03 SN-126 95.1%	3.06E-03 SN-126 95.6%	1.12E-04 CS-135 76.7%	9.97E-05 CS-135 76.7%	7.76E-05 CS-135 76.7%
1.00E+04	6.26E+00 AM-243 99.4%	4.56E+00 AM-243 99.5%	4.09E+00 AM-243 99.7%	4.65E+00 AM-243 99.8%	2.01E-03 SN-126 95.0%	1.84E-03 SN-126 95.4%	1.79E-03 SN-126 95.9%	1.84E-03 SN-126 96.7%	2.01E-03 SN-126 97.3%	4.24E-05 CS-135 85.0%

Table 5.10

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
7500 Years After Repository Sealing

Drill Hits Waste

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.53E-03 CS-135 75.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.53E-03 CS-135 75.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.52E-03 CS-135 75.1%	9.63E-04 CS-135 75.1%	6.82E-04 CS-135 75.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.28E-02 SN-126 93.4%	9.57E-04 CS-135 75.3%	6.78E-04 CS-135 75.3%	4.82E-04 CS-135 75.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.26E-02 SN-126 93.4%	9.45E-04 CS-135 75.5%	6.69E-04 CS-135 75.5%	4.76E-04 CS-135 75.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.19E-02 SN-126 93.4%	1.40E-02 SN-126 93.5%	1.01E-02 SN-126 93.6%	4.58E-04 CS-135 76.1%	2.94E-04 CS-135 76.1%	2.43E-04 CS-135 76.1%	2.13E-04 CS-135 76.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	2.38E+01 AM-243 99.7%	1.33E-02 SN-126 93.6%	9.60E-03 SN-126 93.7%	7.10E-03 SN-126 93.9%	2.76E-04 CS-135 77.1%	2.28E-04 CS-135 77.1%	2.00E-04 CS-135 77.1%	1.67E-04 CS-135 77.1%	1.48E-04 CS-135 77.1%	0.0 NONE 0.0%
2.00E+03	1.97E+01 AM-243 99.7%	1.19E-02 SN-126 93.7%	8.62E-03 SN-126 93.8%	6.37E-03 SN-126 94.0%	2.43E-04 CS-135 79.0%	2.01E-04 CS-135 79.0%	1.76E-04 CS-135 79.0%	1.47E-04 CS-135 79.0%	1.31E-04 CS-135 79.0%	1.02E-04 CS-135 79.0%
5.00E+03	1.11E+01 AM-243 99.6%	8.11E+00 AM-243 99.7%	7.27E+00 AM-243 99.8%	4.61E-03 SN-126 94.3%	3.34E-03 SN-126 94.9%	3.06E-03 SN-126 95.4%	2.97E-03 SN-126 95.9%	1.03E-04 CS-135 83.9%	9.11E-05 CS-135 83.9%	7.08E-05 CS-135 84.0%
1.00E+04	4.31E+00 AM-243 99.2%	3.14E+00 AM-243 99.3%	2.81E+00 AM-243 99.5%	3.19E+00 AM-243 99.8%	1.96E-03 SN-126 95.1%	1.79E-03 SN-126 95.6%	1.74E-03 SN-126 96.0%	1.79E-03 SN-126 96.7%	1.95E-03 SN-126 97.4%	4.02E-05 CS-135 89.7%

since repository sealing, has decreased by a factor of about 700. In Table 5.10 the highest dose rate is 24 rem/yr, 1000 years after drilling, almost entirely from Am-243.

Table 5.11 shows the area contaminated by this direct hit drilling release 200, 1000, 3350, and 7500 years after sealing. Contaminated areas occur before 1000 years only for the 200-year drilling event; Sr-90 is the chief contributor. For later drilling events, areas contaminated to give dose rates above 0.5 rem/yr appear 1000 years after drilling as americium nuclides arrive. These areas increase and reach a maximum 10,000 years after drilling. The largest areas contaminated to give more than 0.5 rem/yr do not differ much for the four drilling event times, ranging from 6.2 ha (62,000 square meters) for the 200-year event to 5.3 ha for the 7500-year drilling event. For all four cases, the maximum area contaminated is a little less than one percent of the 800-hectare area of the repository. Areas contaminated above 5 rem/yr also appear 1,000 years after drilling and reach their largest extent 5,000 or 10,000 years after drilling, after which they decrease rapidly. For the 200-year and 1000-year drilling events, the maximum areas contaminated to give more than 5 rem/yr are 1.7 and 1.3 ha, respectively, at 10,000 years after the drilling. For the 3350-year and 7500-year drilling events, the maximum areas contaminated are one ha and 0.75 ha, respectively, at 5000 years after the drilling. Small areas contaminated more severely, above 50 and 500 rem/yr, also appear at 1000 years after drilling but decrease rapidly as the nuclides diffuse to lower concentrations.

5.1.2 Brine pocket

The results and tables discussed to this point assume that a drill hits the waste directly. Even if the drill does not hit waste, it may hit one of several brine pockets in a salt repository which result from water leaks through the shaft seals (SmC 82, ADL 79). The brine pocket in the reference case is assumed be in contact with waste from two

Table 5.11

Area (ha*) of the Aquifer Contaminated Above the Specified Dose Rate Levels Following a Direct Drilling Hit on Waste

Time After Drill (yr)	200 years after sealing: 0.5 rem/yr	5.0	50	500	1000 years after sealing: 0.5 rem/yr	5.0	50	500
10	0.14	0.10	0.05	0	0	0	0	0
20	0.13	0.10	0.04	0	0	0	0	0
50	1.3	0.80	0	0	0	0	0	0
100	2.8	0.45	0	0	0	0	0	0
200	0.26	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0
1,000	0.36	0.30	0.24	0.15	0.33	0.27	0.20	0.06
2,000	0.32	0.26	0.18	0	0.30	0.23	0.13	0
5,000	2.1	1.3	0	0	2.1	1.2	0	0
10,000	6.2	1.7	0	0	6.1	1.3	0	0

Time After Drill (yr)	3350 years after sealing: 0.5 rem/yr	5.0	50	500	7500 years after sealing: 0.5 rem/yr	5.0	50	500
10	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0
1,000	0.27	0.19	0.02	0	0.24	0.16	0	0
2,000	0.25	0.17	0	0	0.24	0.14	0	0
5,000	2.0	1.0	0	0	1.9	0.75	0	0
10,000	5.8	0.06	0	0	5.3	0	0	0

*1 hectare (ha) = 10^4 square meters

canisters and is 0.06 m^3 in volume (SmC 82). Table 5.12 gives the annual dose rates from drilling into a brine pocket 1000 years afer repository sealing. The highest dose rate is 1150 rem/yr at 20 meters and 1000 years after the drilling. This is almost twice the value of 625 rem/yr for the direct hit case (Table 5.7) All annual dose rates in Table 5.12 are approximately twice those in Table 5.7, reflecting the situation when the brine pocket is in contact with waste from two canisters. The annual dose rates from drilling into a brine pocket 200 years, 3350 years, and 7500 years after repository sealing (Tables 5.13, 5.14, and 5.15) are approximately twice those in the corresponding direct hit cases in Tables 5.8, 5.9, and 5.10. The same nuclides are significant and the discussion in Section 5.1.1 applies here as well. Table 5.16 shows the groundwater areas contaminated after drilling into a brine pocket. The general spread of contamination, which is such that the less heavily contaminated areas become larger up to 10,000 years after drilling, is similar to that for the direct hit case (Table 5.11). It is noteworthy that the areas contaminated by drilling into a brine pocket are only slightly larger than those contaminated by a direct hit, although the annual dose rates at a given point are almost twice as large.

5.1.3 Granite tank

If a drill penetrates into a granite repository, there will be a release of nuclides even if the drill does not hit waste. Water that has filled the void volume of 2 x 10^6 m^3 in the repository becomes contaminated by leaching and dissolving of the waste after the canisters fail at 500 years after repository sealing. The earliest event time we considered was 500 years after sealing (ADL 79). The releases from any earlier drilling would be zero until the canisters fail at 500 years.

Table 5.17 gives the annual dose rates resulting from drilling into the granite tank 1000 years after sealing. Cs-135 and Sn-126 give small doses in the first 1000 years. At 1000 years, Am-241 appears at 20 meters as the major contributor to a dose rate of 1800 rem/yr.

Table 5.12

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.57E-03 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	3.59E-03 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	3.58E-03 CS-135 58.7%	2.26E-03 CS-135 58.7%	1.60E-03 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	4.44E-02 SN-126 92.0%	2.25E-03 CS-135 58.8%	1.59E-03 CS-135 58.8%	1.13E-03 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	4.39E-02 SN-126 92.0%	2.21E-03 CS-135 59.1%	1.57E-03 CS-135 59.1%	1.11E-03 CS-135 59.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	4.25E-02 SN-126 92.1%	2.73E-02 SN-126 92.2%	1.97E-02 SN-126 92.4%	1.07E-03 CS-135 60.0%	6.85E-04 CS-135 60.0%	5.65E-04 CS-135 60.0%	4.95E-04 CS-135 60.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.15E+03 AM-241 93.1%	2.58E-02 SN-126 92.4%	1.87E-02 SN-126 92.5%	1.38E-02 SN-126 92.8%	6.35E-04 CS-135 61.4%	5.26E-04 CS-135 61.4%	4.61E-04 CS-135 61.4%	3.85E-04 CS-135 61.4%	3.42E-04 CS-135 61.4%	0.0 NONE 0.0%
2.00E+03	2.78E+02 AM-241 76.6%	2.30E-02 SN-126 92.6%	1.67E-02 SN-126 92.7%	1.24E-02 SN-126 93.0%	5.48E-04 CS-135 64.1%	4.54E-04 CS-135 64.1%	3.97E-04 CS-135 64.1%	3.33E-04 CS-135 64.1%	2.96E-04 CS-135 64.1%	2.30E-04 CS-135 64.1%
5.00E+03	3.80E+01 AM-243 95.5%	2.79E+01 AM-243 95.5%	2.51E+01 AM-243 95.5%	8.82E-03 SN-126 93.6%	6.44E-03 SN-126 94.4%	5.90E-03 SN-126 95.0%	5.72E-03 SN-126 95.4%	2.19E-04 CS-135 71.7%	1.94E-04 CS-135 71.7%	1.52E-04 CS-135 71.7%
1.00E+04	1.40E+01 AM-243 99.7%	1.04E+01 AM-243 99.7%	9.15E+00 AM-243 99.8%	1.05E+01 AM-243 99.9%	3.77E-03 SN-126 94.9%	3.41E-03 SN-126 95.3%	3.30E-03 SN-126 95.8%	3.44E-03 SN-126 96.6%	3.74E-03 SN-126 97.2%	8.06E-05 CS-135 81.7%

Table 5.13

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
200 Years After Repository Sealing

Drill Hits Repository Water

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.00E+02 SR -90 76.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.57E+02 SR -90 76.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	7.68E+01 SR -90 76.0%	4.86E+01 SR -90 76.0%	3.45E+01 SR -90 76.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.32E+01 SR -90 75.0%	1.47E+01 SR -90 75.1%	1.04E+01 SR -90 75.1%	7.40E+00 SR -90 75.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.17E+00 SR -90 71.7%	1.35E+00 SR -90 73.2%	9.54E-01 SR -90 73.2%	6.78E-01 SR -90 73.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	4.81E-02 SN-126 88.7%	3.08E-02 SN-126 88.9%	2.23E-02 SN-126 89.1%	1.73E-03 CS-135 40.2%	1.11E-03 CS-135 40.1%	9.13E-04 CS-135 40.1%	8.03E-04 CS-135 40.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	3.97E+03 AM-241 97.7%	2.81E-02 SN-126 92.1%	2.04E-02 SN-126 92.3%	1.51E-02 SN-126 92.6%	7.15E-04 CS-135 59.1%	5.91E-04 CS-135 59.1%	5.18E-04 CS-135 59.1%	4.32E-04 CS-135 59.1%	3.85E-04 CS-135 59.1%	0.0 NONE 0.0%
2.00E+03	8.49E+02 AM-241 91.1%	2.52E-02 SN-126 92.4%	1.82E-02 SN-126 92.5%	1.35E-02 SN-126 92.8%	6.17E-04 CS-135 61.9%	5.10E-04 CS-135 61.9%	4.47E-04 CS-135 61.9%	3.74E-04 CS-135 61.9%	3.32E-04 CS-135 61.9%	2.58E-04 CS-135 61.9%
5.00E+03	4.87E+01 AM-243 87.4%	3.55E+01 AM-243 87.4%	3.19E+01 AM-243 87.4%	9.68E-03 SN-126 93.5%	7.01E-03 SN-126 94.2%	6.43E-03 SN-126 94.9%	6.23E-03 SN-126 95.3%	2.43E-04 CS-135 69.8%	2.17E-04 CS-135 69.8%	1.69E-04 CS-135 69.8%
1.00E+04	1.63E+01 AM-243 99.7%	1.21E+01 AM-243 99.8%	1.06E+01 AM-243 99.8%	1.23E+01 AM-243 99.9%	4.11E-03 SN-126 94.8%	3.71E-03 SN-126 95.3%	3.59E-03 SN-126 95.7%	3.75E-03 SN-126 96.6%	4.07E-03 SN-126 97.2%	8.88E-05 CS-135 80.3%

Table 5.14

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
3350 Years After Repository Sealing

Drill Hits Repository Water

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.47E-03 CS-135 65.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	2.57E-03 CS-135 65.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	2.55E-03 CS-135 65.2%	1.62E-03 CS-135 65.2%	1.15E-03 CS-135 65.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	3.44E-02 SN-126 92.7%	1.61E-03 CS-135 65.3%	1.14E-03 CS-135 65.3%	8.08E-04 CS-135 65.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	3.42E-02 SN-126 92.7%	1.59E-03 CS-135 65.6%	1.12E-03 CS-135 65.6%	8.01E-04 CS-135 65.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	3.31E-02 SN-126 92.8%	2.10E-02 SN-126 92.8%	1.53E-02 SN-126 92.9%	7.68E-04 CS-135 66.4%	4.87E-04 CS-135 66.4%	4.02E-04 CS-135 66.4%	3.55E-04 CS-135 66.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	7.42E+01 AM-243 67.5%	2.00E-02 SN-126 93.0%	1.44E-02 SN-126 93.0%	1.06E-02 SN-126 93.4%	4.57E-04 CS-135 67.7%	3.76E-04 CS-135 67.7%	3.28E-04 CS-135 67.7%	2.75E-04 CS-135 67.7%	2.44E-04 CS-135 67.7%	0.0 NONE 0.0%
2.00E+03	4.55E+01 AM-243 89.5%	1.79E-02 SN-126 93.2%	1.29E-02 SN-126 93.3%	9.41E-03 SN-126 93.4%	3.97E-04 CS-135 70.1%	3.24E-04 CS-135 70.1%	2.88E-04 CS-135 70.1%	2.38E-04 CS-135 70.1%	2.10E-04 CS-135 70.1%	1.66E-04 CS-135 70.1%
5.00E+03	2.34E+01 AM-243 99.6%	1.71E+01 AM-243 99.7%	1.54E+01 AM-243 99.7%	6.87E-03 SN-126 93.9%	4.98E-03 SN-126 94.6%	4.54E-03 SN-126 95.2%	4.44E-03 SN-126 95.6%	1.61E-04 CS-135 76.8%	1.44E-04 CS-135 76.8%	1.10E-04 CS-135 76.8%
1.00E+04	8.96E+00 AM-243 99.6%	6.63E+00 AM-243 99.6%	5.84E+00 AM-243 99.7%	6.76E+00 AM-243 99.8%	2.93E-03 SN-126 95.0%	2.65E-03 SN-126 95.5%	2.56E-03 SN-126 95.9%	2.65E-03 SN-126 96.7%	2.92E-03 SN-126 97.3%	6.11E-05 CS-135 85.1%

Table 5.15

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
7500 Years After Repository Sealing

Drill Hits Repository Water

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.35E-03 CS-135 75.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.45E-03 CS-135 75.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.44E-03 CS-135 75.1%	9.08E-04 CS-135 75.1%	6.48E-04 CS-135 75.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.16E-02 SN-126 93.4%	9.10E-04 CS-135 75.2%	6.45E-04 CS-135 75.2%	4.57E-04 CS-135 75.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.14E-02 SN-126 93.4%	7.45E-04 CS-135 75.4%	6.36E-04 CS-135 75.5%	4.52E-04 CS-135 75.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.08E-02 SN-126 93.5%	1.31E-02 SN-126 95.0%	9.71E-03 SN-126 93.7%	4.35E-04 CS-135 76.1%	2.79E-04 CS-135 76.1%	2.30E-04 CS-135 76.1%	2.04E-04 CS-135 76.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	2.27E+01 AM-243 99.6%	1.27E-02 SN-126 93;6%	9.00E-03 SN-126 95.1%	6.77E-03 SN-126 94.0%	2.65E-04 CS-135 77.1%	2.14E-04 CS-135 77.1%	1.90E-04 CS-135 77.1%	1.59E-04 CS-135 77.1%	1.41E-04 CS-135 77.1%	0.0 NONE 0.0%
2.00E+03	1.86E+01 AM-243 99.7%	1.14E-02 SN-126 93.7%	8.25E-03 SN-126 93.8%	5.96E-03 SN-126 95.3%	2.33E-04 CS-135 79.0%	1.55E-04 CS-135 79.0%	1.69E-04 CS-135 79.0%	1.39E-04 CS-135 79.0%	1.24E-04 CS-135 79.0%	9.68E-05 CS-135 79.0%
5.00E+03	1.06E+01 AM-243 99.6%	7.73E+00 AM-243 99.7%	6.92E+00 AM-243 99.8%	4.40E-03 SN-126 94.2%	3.18E-03 SN-126 94.9%	2.45E-03 SN-126 94.6%	2.83E-03 SN-126 95.9%	9.73E-05 CS-135 83.9%	8.68E-05 CS-135 83.9%	6.68E-05 CS-135 84.0%
1.00E+04	4.08E+00 AM-243 99.1%	3.01E+00 AM-243 99.3%	2.66E+00 AM-243 99.5%	3.04E+00 AM-243 99.7%	1.88E-03 SN-126 95.1%	1.69E-03 SN-126 95.5%	1.64E-03 SN-126 96.0%	1.70E-03 SN-126 96.8%	1.86E-03 SN-126 97.4%	3.83E-05 CS-135 89.6%

Table 5.16

Area (ha*) of the Aquifer Contaminated
Above the Specified Dose Rate Levels
Following Drilling into a Brine Pocket

Time After Drill (yr)	200 years after sealing: 0.5	5	50	500	1000 years after sealing: 0.5	5	50	500
	Dose Levels (rem/yr)				Dose Levels (rem/yr)			
10	0.14	0.11	0.07	0	0	0	0	0
20	0.14	0.11	0.06	0	0	0	0	0
50	1.4	0.96	0.08	0	0	0	0	0
100	3.2	1.5	0	0	0	0	0	0
200	1.40	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0
1,000	0.37	0.32	0.26	0.18	0.34	0.29	0.22	0.11
2,000	0.34	0.28	0.21	0.09	0.31	0.25	0.16	0
5,000	2.3	1.6	0	0	2.31	1.5	0	0
10,000	7.0	3.7	0	0	6.8	3.3	0	0

Time After Drill (yr)	3350 years after sealing: 0.5	5	50	500	7500 years after sealing: 0.5	5	50	500
10	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0
1,000	0.28	0.20	0.08	0	0.24	0.15	0	0
2,000	0.26	0.18	0	0	0.24	0.14	0	0
5,000	2.1	1.2	0	0	1.9	0.71	0	0
10,000	6.3	2.1	0	0	5.2	0	0	0

*1 hectare (ha) = 10^4 square meters

Table 5.17

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides Released by Borehole Drilling in GRANITE 1000 Years After Repository Sealing

Drill Hits Repository Water

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	5.40E-03 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	5.47E-03 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	5.66E-03 CS-135 58.8%	3.52E-03 CS-135 58.8%	2.42E-03 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	6.78E-02 SN-126 91.2%	3.72E-03 CS-135 58.9%	2.56E-03 CS-135 58.9%	1.71E-03 CS-135 58.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	7.57E-02 SN-126 91.4%	4.06E-03 CS-135 59.2%	2.82E-03 CS-135 59.2%	1.90E-03 CS-135 59.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	9.34E-02 SN-126 91.8%	5.46E-02 SN-126 91.2%	3.16E-02 SN-126 89.3%	2.33E-03 CS-135 60.1%	1.35E-03 CS-135 60.1%	1.00E-03 CS-135 60.1%	7.68E-04 CS-135 60.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.83E+03 AM-241 93.1%	6.75E-02 SN-126 91.9%	4.43E-02 SN-126 91.3%	2.32E-02 SN-126 88.3%	1.65E-03 CS-135 61.5%	1.30E-03 CS-135 61.5%	1.08E-03 CS-135 61.5%	7.75E-04 CS-135 61.5%	5.46E-04 CS-135 61.5%	0.0 NONE 0.0%
2.00E+03	7.93E+02 AM-241 76.6%	7.64E-02 SN-126 92.5%	5.34E-02 SN-126 92.4%	3.58E-02 SN-126 91.9%	1.81E-03 CS-135 64.2%	1.47E-03 CS-135 64.2%	1.27E-03 CS-135 64.2%	1.01E-03 CS-135 64.2%	8.44E-04 CS-135 64.2%	3.89E-04 CS-135 64.2%
5.00E+03	1.37E+02 AM-243 95.5%	9.96E+01 AM-243 95.6%	4.67E+01 AM-243 99.6%	3.16E-02 SN-126 93.9%	2.29E-02 SN-126 94.6%	1.85E-02 SN-126 94.4%	1.15E-02 SN-126 92.0%	7.77E-04 CS-135 71.8%	6.96E-04 CS-135 71.8%	5.49E-04 CS-135 71.8%
1.00E+04	2.96E+01 AM-243 99.9%	2.64E+01 AM-243 99.9%	3.06E+01 AM-243 99.9%	2.40E+01 AM-243 99.9%	9.48E-03 SN-126 96.2%	9.98E-03 SN-126 96.9%	1.09E-02 SN-126 97.5%	1.22E-02 SN-126 98.1%	8.53E-03 SN-126 97.4%	1.94E-04 CS-135 81.9%

Sn-126 and Cs-135 have traveled further from the release site. The maximum dose occurs at the 1000-year dose time and the major contributor is Am-241.

When drilling occurs 500 years after repository sealing (Table 5.18) there are some small annual dose rates before 1000 years later, the major contributors being strontium-90 (Sr-90) for the first 100 years and Sn-126 after that. The Sr-90 contribution is much less than it was for the direct hit and brine pocket cases at 200 years because most of this nuclide (and also most of the Cs-137) has decayed in the approximately 17 half-lives since repository sealing. The Am-241 appears at 20 meters and 1000 years as the major contributor to a dose rate of 480 rem/yr. This dose rate is much smaller than the corresponding one for the 1000-year drilling event because there has been much less time for Am-241 to be leached from the waste into the repository water. In both cases, the Am-241 and -243 has taken 950 years to travel 20 meters, and therefore left the repository 50 years after the drilling. In the 500-year drilling event, the total time for leaching was 50 years; in the 1000-year drilling event, it was 550 years. The additional leaching of Am-241 has more than compensated for the decay of that nuclide during the 500 years.

Tables 5.19 and 5.20 give the annual dose rates from drilling into the granite tank 3350 and 7500 years after sealing. The highest dose rates are lower than those for 1000 years, 260 and 66 rem/yr, respectively. This reduction is caused by the decay of Am-241. The additional leaching of Am-243 into the tank before the drilling event keeps the dose rate from becoming very small. The behavior of nuclides after a few thousand years post-event are similar for all four drilling times.

The maximum contamination from Am-241 occurs from drilling 1140 years after the repository is sealed. We calculated this maximum time by setting the derivative ($\partial C/\partial t$) in equation 4.11 equal to zero. For all events after 1140 years, the size of all contaminated areas will fall as the concentration of Am-241 drops, because Am-241 is the largest contributor.

Table 5.18

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
500 Years After Repository Sealing

Drill Hits Repository Water

TIME (yr)	DISTANCE (meters)									
	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.21E-04 SR -90 68.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	5.48E-03 SR -90 68.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.04E-02 SR -90 66.0%	4.32E-03 SR -90 66.0%	2.85E-04 SR -90 65.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	8.62E-03 SR -90 51.4%	4.18E-03 SR -90 57.1%	2.07E-03 SR -90 57.1%	1.40E-04 SR -90 56.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.12E-02 SN-126 82.2%	2.24E-03 CS-135 40.2%	1.40E-03 CS-135 40.2%	7.07E-04 CS-135 40.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	5.86E-02 SN-126 90.9%	2.76E-02 SN-126 88.0%	4.16E-03 SN-126 45.7%	1.48E-03 CS-135 58.6%	6.74E-04 CS-135 58.6%	3.31E-04 CS-135 58.5%	5.34E-05 CS-135 57.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	4.81E+02 AM-241 96.5%	5.46E-02 SN-126 91.2%	3.16E-02 SN-126 89.3%	4.95E-03 SN-126 52.9%	1.35E-03 CS-135 60.1%	1.00E-03 CS-135 60.1%	7.68E-04 CS-135 60.0%	4.07E-04 CS-135 60.0%	7.17E-05 CS-135 59.7%	0.0 NONE 0.0%
2.00E+03	1.30E+03 AM-241 87.0%	7.39E-02 SN-126 92.2%	5.05E-02 SN-126 92.0%	3.16E-02 SN-126 90.9%	1.78E-03 CS-135 62.9%	1.43E-03 CS-135 62.9%	1.21E-03 CS-135 62.9%	9.40E-04 CS-135 62.9%	7.52E-04 CS-135 62.9%	9.27E-05 CS-135 62.7%
5.00E+03	1.59E+02 AM-243 91.4%	1.11E+02 AM-243 91.4%	2.25E+01 AM-243 99.1%	3.39E-02 SN-126 93.7%	2.35E-02 SN-126 94.1%	1.74E-02 SN-126 93.5%	5.88E-03 SN-126 82.9%	8.46E-04 CS-135 70.6%	7.54E-04 CS-135 70.6%	5.78E-04 CS-135 70.6%
1.00E+04	3.50E+01 AM-243 99.9%	3.09E+01 AM-243 99.9%	3.50E+01 AM-243 99.9%	1.68E+01 AM-243 99.9%	1.07E-02 SN-126 96.1%	1.11E-02 SN-126 96.8%	1.19E-02 SN-126 97.4%	1.25E-02 SN-126 97.8%	5.82E-03 SN-126 95.7%	2.20E-04 CS-135 81.0%

Table 5.19

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
3350 Years After Repository Sealing

Drill Hits Repository Water

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	8.95E-03 CS-135 65.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	8.94E-03 CS-135 65.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	8.92E-03 CS-135 65.3%	5.65E-03 CS-135 65.3%	4.00E-03 CS-135 65.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.20E-01 SN-126 92.6%	5.63E-03 CS-135 65.4%	3.98E-03 CS-135 65.4%	2.82E-03 CS-135 65.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.20E-01 SN-126 92.6%	5.58E-03 CS-135 65.7%	3.95E-03 CS-135 65.7%	2.80E-03 CS-135 65.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.18E-01 SN-126 92.7%	7.50E-02 SN-126 92.8%	5.36E-02 SN-126 92.8%	2.72E-03 CS-135 66.5%	1.74E-03 CS-135 66.5%	1.43E-03 CS-135 66.5%	1.24E-03 CS-135 66.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	2.61E+02 AM-243 67.5%	7.21E-02 SN-126 92.9%	5.19E-02 SN-126 93.0%	3.76E-02 SN-126 93.2%	1.64E-03 CS-135 67.8%	1.36E-03 CS-135 67.8%	1.19E-03 CS-135 67.8%	9.82E-04 CS-135 67.8%	8.59E-04 CS-135 67.8%	0.0 NONE 0.0%
2.00E+03	1.67E+02 AM-243 89.6%	6.35E-02 SN-126 93.2%	4.63E-02 SN-126 93.4%	3.45E-02 SN-126 93.7%	1.41E-03 CS-135 70.3%	1.17E-03 CS-135 70.3%	1.03E-03 CS-135 70.3%	8.67E-04 CS-135 70.3%	7.71E-04 CS-135 70.3%	5.85E-04 CS-135 70.3%
5.00E+03	6.95E+01 AM-243 99.8%	5.79E+01 AM-243 99.8%	5.46E+01 AM-243 99.9%	2.03E-02 SN-126 94.5%	1.67E-02 SN-126 95.6%	1.63E-02 SN-126 96.2%	1.57E-02 SN-126 96.5%	4.68E-04 CS-135 77.0%	4.27E-04 CS-135 77.0%	3.64E-04 CS-135 77.0%
1.00E+04	1.31E+01 AM-243 99.9%	1.20E+01 AM-243 99.9%	1.52E+01 AM-243 99.9%	2.42E+01 AM-243 100.0%	5.24E-03 SN-126 96.4%	5.72E-03 SN-126 97.2%	6.53E-03 SN-126 97.8%	8.68E-03 SN-126 98.6%	1.03E-02 SN-126 98.9%	1.03E-04 CS-135 85.5%

Table 5.20

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
7500 Years After Repository Sealing

Drill Hits Repository Water

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	4.27E-03 CS-135 75.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	4.26E-03 CS-135 75.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	4.23E-03 CS-135 75.3%	2.68E-03 CS-135 75.3%	1.91E-03 CS-135 75.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	6.39E-02 SN-126 93.5%	2.65E-03 CS-135 75.4%	1.88E-03 CS-135 75.4%	1.35E-03 CS-135 75.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	6.25E-02 SN-126 93.5%	2.59E-03 CS-135 75.6%	1.84E-03 CS-135 75.6%	1.31E-03 CS-135 75.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	5.84E-02 SN-126 93.5%	3.80E-02 SN-126 93.7%	2.82E-02 SN-126 93.9%	1.22E-03 CS-135 76.3%	7.97E-04 CS-135 76.3%	6.68E-04 CS-135 76.3%	5.93E-04 CS-135 76.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	6.64E+01 AM-243 99.8%	3.39E-02 SN-126 93.7%	2.52E-02 SN-126 94.0%	1.97E-02 SN-126 94.5%	7.04E-04 CS-135 77.3%	5.90E-04 CS-135 77.3%	5.25E-04 CS-135 77.3%	4.52E-04 CS-135 77.3%	4.12E-04 CS-135 77.3%	0.0 NONE 0.0%
2.00E+03	4.86E+01 AM-243 99.9%	2.67E-02 SN-126 93.9%	1.99E-02 SN-126 94.2%	1.56E-02 SN-126 94.7%	5.44E-04 CS-135 79.2%	4.57E-04 CS-135 79.2%	4.07E-04 CS-135 79.2%	3.52E-04 CS-135 79.2%	3.22E-04 CS-135 79.2%	2.81E-04 CS-135 79.2%
5.00E+03	1.77E+01 AM-243 99.9%	1.61E+01 AM-243 99.9%	1.98E+01 AM-243 100.0%	7.28E-03 SN-126 95.0%	6.53E-03 SN-126 96.3%	7.05E-03 SN-126 97.1%	7.94E-03 SN-126 97.7%	1.57E-04 CS-135 84.3%	1.44E-04 CS-135 84.3%	1.30E-04 CS-135 84.3%
1.00E+04	2.85E+00 AM-243 99.8%	2.70E+00 AM-243 99.9%	3.66E+00 AM-243 99.9%	8.45E+00 AM-243 100.0%	1.66E-03 SN-126 96.6%	1.87E-03 SN-126 97.5%	2.22E-03 SN-126 98.1%	3.35E-03 SN-126 98.9%	5.07E-03 SN-126 99.3%	3.16E-05 CS-135 90.2%

Table 5.21 shows the extent of aquifer contamination after drilling into the granite tank. The general pattern of the spread of contamination at dose rates above 0.5 and 5 rem/yr is similar to that seen for the direct hit and brine pocket cases, although the contaminated areas are somewhat larger, and contamination for the 500-year event is markedly less than for the 1000-year event. Areas contaminated to the 50- and 500-rem/yr levels are somewhat larger and the contamination is more persistent than for the other two cases.

5.2 Releases to the Aquifer due to Faulting

For faulting events (Section 4.2), we used a different mathematical description and coordinate system. We selected the positive x-axis in the direction of aquifer flow, which is parallel to the assigned fault direction. The origin is at one end of the repository and $x = 4000$ meters at the other end. The mathematical description is given in Chapter 4 where the event is modeled by integrating releases from a line source, equivalent to a large number of borehole drilling events. We assumed that the fault line intersects wastes from one row of canisters and ruptures all of the canisters if they are still intact in that row. The wastes then leach or dissolve into the groundwater.

5.2.1 Fault hits waste

For this case, the same pathway characteristics were assigned to both the bedded salt and granite repositories. Table 5.22 gives the annual dose rates at the preselected distances and times for a faulting event at 1000 years after repository sealing that directly affects the waste from a row of canisters. Sn-126 is the predominant nuclide until 50 years after the faulting because the americium nuclides take 50 years to travel one meter. Am-241 is dominant from 50 to 2000 years. From 5000 to 10,000 years, Am-243 is the most important nuclide. The highest dose rate is about 600 rem/yr at 500 years. After 500 years, the dose rates decline as the decay of the nuclides outweighs the contributions from waste further away from the dose point. Only the two americium isotopes give substantial doses. Doses from americium increase for

Table 5.21

Area of the Aquifer Contaminated
Above the Specified Dose Rate Levels
Following Drilling into the Granite Tank

Time After Drill (yr)	Dose Limits (rem/yr) 0.5	5	50	500	Dose Limits (rem/yr) 0.5	5	50	500
	200 years after sealing				1000 years after sealing			
0-500	0	0	0	0	0	0	0	0
1,000	0.32	0.26	0.19	0	0.36	0.30	0.24	0.14
2,000	0.35	0.29	0.22	0.12	0.34	0.28	0.21	0.08
5,000	2.4	1.6	0.38	0	2.5	1.8	0.36	0
10,000	7.5	4.6	0	0	7.8	5.0	0	0
	3350 years after sealing				7500 years after sealing			
0-500	0	0	0	0	0	0	0	0
1,000	0.31	0.25	0.16	0	0.27	0.20	0.06	0
2,000	0.30	0.23	0.14	0	0.27	0.19	0	0
5,000	2.5	1.8	0.39	0	2.2	1.3	0	0
10,000	7.5	4.6	0	0	6.2	2.0	0	0

*1 hectare (ha) = 10^4 square meters

Table 5.22

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Waste Directly Affected

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	5.30E-03 SN-126 42.2%	5.40E-03 SN-126 41.5%	5.40E-03 SN-126 41.5%	5.40E-03 SN-126 41.5%	5.40E-03 SN-126 41.5%	5.40E-03 SN-126 41.5%	5.40E-03 SN-126 41.5%	5.40E-03 SN-126 41.5%	5.40E-03 SN-126 41.5%	5.40E-03 SN-126 41.5%
2.00E+01	8.28E-03 SN-126 63.1%	1.01E-02 SN-126 51.9%	1.01E-02 SN-126 51.9%	1.01E-02 SN-126 51.9%	1.01E-02 SN-126 51.9%	1.01E-02 SN-126 51.9%	1.01E-02 SN-126 51.9%	1.01E-02 SN-126 51.9%	1.01E-02 SN-126 51.9%	1.01E-02 SN-126 51.9%
5.00E+01	1.38E+01 AM-241 97.3%	1.38E+01 AM-241 97.3%	1.38E+01 AM-241 97.3%	1.38E+01 AM-241 97.3%	1.38E+01 AM-241 97.3%	1.38E+01 AM-241 97.3%	1.38E+01 AM-241 97.3%	1.38E+01 AM-241 97.3%	1.38E+01 AM-241 97.3%	1.38E+01 AM-241 97.3%
1.00E+02	2.32E+02 AM-241 97.2%	2.32E+02 AM-241 97.2%	2.32E+02 AM-241 97.2%	2.32E+02 AM-241 97.2%	2.32E+02 AM-241 97.2%	2.32E+02 AM-241 97.2%	2.32E+02 AM-241 97.2%	2.32E+02 AM-241 97.2%	2.32E+02 AM-241 97.2%	2.32E+02 AM-241 97.2%
2.00E+02	4.61E+02 AM-241 96.8%	4.61E+02 AM-241 96.8%	4.61E+02 AM-241 96.8%	4.61E+02 AM-241 96.8%	4.61E+02 AM-241 96.8%	4.61E+02 AM-241 96.8%	4.61E+02 AM-241 96.8%	4.61E+02 AM-241 96.8%	4.61E+02 AM-241 96.8%	4.61E+02 AM-241 96.8%
5.00E+02	6.10E+02 AM-241 95.1%	6.10E+02 AM-241 95.1%	6.10E+02 AM-241 95.1%	6.10E+02 AM-241 95.1%	6.10E+02 AM-241 95.1%	6.10E+02 AM-241 95.1%	6.10E+02 AM-241 95.1%	6.10E+02 AM-241 95.1%	6.10E+02 AM-241 95.1%	6.10E+02 AM-241 95.1%
1.00E+03	4.37E+02 AM-241 90.2%	4.50E+02 AM-241 90.2%	4.50E+02 AM-241 90.2%	4.50E+02 AM-241 90.2%	4.50E+02 AM-241 90.2%	4.50E+02 AM-241 90.2%	4.50E+02 AM-241 90.2%	4.50E+02 AM-241 90.2%	4.50E+02 AM-241 90.2%	4.50E+02 AM-241 90.2%
2.00E+03	1.16E+02 AM-241 67.7%	1.77E+02 AM-241 67.6%	1.77E+02 AM-241 67.6%	1.77E+02 AM-241 67.6%	1.77E+02 AM-241 67.6%	1.77E+02 AM-241 67.6%	1.77E+02 AM-241 67.6%	1.77E+02 AM-241 67.6%	1.77E+02 AM-241 67.6%	1.77E+02 AM-241 67.6%
5.00E+03	2.77E+01 AM-243 48.9%	4.64E+01 AM-243 48.6%	6.42E+01 AM-243 48.2%	6.55E+01 AM-243 48.2%	6.55E+01 AM-243 48.2%	6.56E+01 AM-243 48.2%	6.56E+01 AM-243 48.2%	6.56E+01 AM-243 48.2%	6.56E+01 AM-243 48.2%	6.56E+01 AM-243 48.1%
1.00E+04	1.28E+01 AM-243 40.8%	2.15E+01 AM-243 40.5%	2.99E+01 AM-243 40.0%	3.88E+01 AM-243 39.1%	3.94E+01 AM-243 39.1%	3.94E+01 AM-243 39.0%	3.94E+01 AM-243 39.0%	3.94E+01 AM-243 39.0%	3.94E+01 AM-243 39.0%	3.95E+01 AM-243 39.0%

the first 500 years, representing the ability of these nuclides to reach the dose points from greater distances.

From 50 to 500 years, the annual dose rates are the same over the entire length of the repository. The annual dose rates at each point represent contributions from a very short distance because the important Am-241 travels only 10.5 meters in 500 years. After this time, the points close to the upstream (or upgradient) end of the repository show slightly lower dose rates. For example, at 5000 years, the annual dose rates at 20, 50 and 100 meters are slightly less than those at longer distances. In 5000 years, americium travels 105 meters. As a result, all the annual dose rates from 200 to 4000 meters are the same because they represent contributions from as far away as 105 meters. The annual dose rates at 20, 50 and 100 meters are lower because there is no waste beyond the edge of the repository that would be a source for these points at this time.

Tables 5.23, 5.24, and 5.25 give the annual dose rates from faulting at 200, 3350, and 7500 years after repository sealing. The dose rates in this case decrease for later faulting; for example, the highest dose rates at 4000 meters are 1970, 600, 36, and 21 rem/yr for faulting at 200, 1000, 3350, and 7500 years, respectively. The 200-year event dose rates are dominated by Sr-90 for 50 years. The maximum doses from the Sr-90 occur at (4000 m, 20 yr), 74 rem/yr. The Am-241 takes between 50 and 100 years to reach the aquifer.

Table 5.24 shows the same important nuclides at 3350 years as at 1000 years. For the 7500-year event, Am-243 is the only important americium isotope because the Am-241 has decayed. Other contaminants at 7500 years are the same as for the other event times. No area tables are calculated for the faulting releases.

5.2.2 Faulting through a granite tank or brine pocket

In this scenario, only the granite repository is examined because the initial release from the granite tank would be greater than from a brine pocket because of its greater volume and also later in time the

Table 5.23

Dsoe Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
200 Years After Repository Sealing

Waste Directly Affected

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	7.80E+01 SR -90 76.7%	8.05E+01 SR -90 76.7%	8.05E+01 SR -90 76.7%	8.05E+01 SR -90 76.7%	8.05E+01 SR -90 76.7%	8.05E+01 SR -90 76.7%	8.05E+01 SR -90 76.7%	8.05E+01 SR -90 76.7%	8.05E+01 SR -90 76.7%	8.05E+01 SR -90 76.7%
2.00E+01	6.14E+01 SR -90 76.5%	9.71E+01 SR -90 76.5%	9.71E+01 SR -90 76.5%	9.71E+01 SR -90 76.5%	9.71E+01 SR -90 76.5%	9.71E+01 SR -90 76.5%	9.71E+01 SR -90 76.5%	9.71E+01 SR -90 76.5%	9.71E+01 SR -90 76.5%	9.71E+01 SR -90 76.5%
5.00E+01	7.56E+01 AM-241 59.7%	9.81E+01 AM-241 46.0%	1.23E+02 SR -90 47.9%	1.25E+02 SR -90 48.3%	1.25E+02 SR -90 48.3%	1.25E+02 SR -90 48.3%	1.25E+02 SR -90 48.3%	1.25E+02 SR -90 48.3%	1.25E+02 SR -90 48.3%	1.25E+02 SR -90 48.3%
1.00E+02	7.73E+02 AM-241 97.7%	7.80E+02 AM-241 96.9%	7.88E+02 AM-241 95.9%	7.98E+02 AM-241 94.7%	7.99E+02 AM-241 94.6%	7.99E+02 AM-241 94.6%	7.99E+02 AM-241 94.6%	7.99E+02 AM-241 94.6%	7.99E+02 AM-241 94.6%	7.99E+02 AM-241 94.6%
2.00E+02	1.51E+03 AM-241 98.8%	1.51E+03 AM-241 98.8%	1.52E+03 AM-241 98.7%	1.52E+03 AM-241 98.7%	1.52E+03 AM-241 98.6%	1.52E+03 AM-241 98.6%	1.52E+03 AM-241 98.6%	1.52E+03 AM-241 98.6%	1.52E+03 AM-241 98.6%	1.52E+03 AM-241 98.6%
5.00E+02	1.98E+03 AM-241 98.4%	1.98E+03 AM-241 98.4%	1.98E+03 AM-241 98.4%	1.98E+03 AM-241 98.4%	1.98E+03 AM-241 98.4%	1.98E+03 AM-241 98.4%	1.98E+03 AM-241 98.4%	1.98E+03 AM-241 98.4%	1.98E+03 AM-241 98.4%	1.98E+03 AM-241 98.4%
1.00E+03	1.37E+03 AM-241 96.7%	1.41E+03 AM-241 96.7%	1.41E+03 AM-241 96.7%	1.41E+03 AM-241 96.7%	1.41E+03 AM-241 96.7%	1.41E+03 AM-241 96.7%	1.41E+03 AM-241 96.7%	1.41E+03 AM-241 96.7%	1.41E+03 AM-241 96.7%	1.41E+03 AM-241 96.7%
2.00E+03	3.03E+02 AM-241 87.0%	4.62E+02 AM-241 87.0%	4.62E+02 AM-241 87.0%	4.62E+02 AM-241 87.0%	4.62E+02 AM-241 87.0%	4.62E+02 AM-241 87.0%	4.62E+02 AM-241 87.0%	4.62E+02 AM-241 87.0%	4.62E+02 AM-241 87.0%	4.62E+02 AM-241 87.0%
5.00E+03	3.02E+01 AM-243 48.2%	5.05E+01 AM-243 48.0%	6.99E+01 AM-243 47.7%	7.13E+01 AM-243 47.6%	7.13E+01 AM-243 47.6%	7.13E+01 AM-243 47.6%	7.14E+01 AM-243 47.6%	7.14E+01 AM-243 47.6%	7.14E+01 AM-243 47.6%	7.14E+01 AM-243 47.6%
1.00E+04	1.35E+01 AM-243 41.5%	2.27E+01 AM-243 41.2%	3.15E+01 AM-243 40.7%	4.09E+01 AM-243 39.9%	4.16E+01 AM-243 39.8%	4.16E+01 AM-243 39.8%	4.16E+01 AM-243 39.8%	4.16E+01 AM-243 39.8%	4.16E+01 AM-243 39.8%	4.16E+01 AM-243 39.8%

Table 5.24

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
3350 Years After Repository Sealing

Waste Directly Affected

TIME (yr)	DISTANCE (meters)									
	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
	5.11E-03	5.20E-03	5.20E-03	5.20E-03	5.20E-03	5.20E-03	5.20E-03	5.20E-03	5.20E-03	5.20E-03
1.00E+01	SN-126	SN-126	SN-126	SN-126	SN-126	SN-126	SN-126	SN-126	SN-126	SN-126
	43.1%	42.3%	42.3%	42.3%	42.3%	42.3%	42.3%	42.3%	42.3%	42.3%
	8.04E-03	9.73E-03	9.73E-03	9.73E-03	9.73E-03	9.73E-03	9.73E-03	9.73E-03	9.73E-03	9.73E-03
2.00E+01	SN-126	SN-126	SN-126	SN-126	SN-126	SN-126	SN-126	SN-126	SN-126	SN-126
	63.9%	52.8%	52.8%	52.8%	52.8%	52.8%	52.8%	52.8%	52.8%	52.8%
	7.05E-01	7.07E-01	7.09E-01	7.09E-01	7.09E-01	7.09E-01	7.09E-01	7.09E-01	7.09E-01	7.09E-01
5.00E+01	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241
	54.5%	54.4%	54.2%	54.2%	54.2%	54.2%	54.2%	54.2%	54.2%	54.2%
	1.20E+01	1.20E+01	1.20E+01	1.20E+01	1.20E+01	1.20E+01	1.20E+01	1.20E+01	1.20E+01	1.20E+01
1.00E+02	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241
	53.7%	53.7%	53.7%	53.7%	53.7%	53.7%	53.7%	53.7%	53.7%	53.7%
	2.55E+01	2.55E+01	2.55E+01	2.55E+01	2.55E+01	2.55E+01	2.55E+01	2.55E+01	2.55E+01	2.55E+01
2.00E+02	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241	AM-241
	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%
	4.24E+01	4.24E+01	4.24E+01	4.24E+01	4.24E+01	4.24E+01	4.24E+01	4.24E+01	4.24E+01	4.24E+01
5.00E+02	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243
	40.0%	39.9%	39.9%	39.9%	39.9%	39.9%	39.9%	39.9%	39.9%	39.9%
	4.83E+01	4.98E+01	4.98E+01	4.98E+01	4.98E+01	4.98E+01	4.98E+01	4.98E+01	4.98E+01	4.98E+01
1.00E+03	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243
	48.6%	48.5%	48.5%	48.5%	48.5%	48.5%	48.5%	48.5%	48.5%	48.5%
	3.52E+01	5.38E+01	5.38E+01	5.39E+01	5.39E+01	5.39E+01	5.39E+01	5.39E+01	5.39E+01	5.39E+01
2.00E+03	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243
	55.1%	54.9%	54.9%	54.9%	54.9%	54.9%	54.8%	54.8%	54.8%	54.8%
	2.32E+01	3.89E+01	5.39E+01	5.51E+01	5.51E+01	5.51E+01	5.51E+01	5.51E+01	5.51E+01	5.51E+01
5.00E+03	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243
	47.2%	46.9%	46.4%	46.3%	46.3%	46.3%	46.3%	46.3%	46.3%	46.3%
	1.10E+01	1.85E+01	2.57E+01	3.35E+01	3.40E+01	3.40E+01	3.40E+01	3.40E+01	3.41E+01	3.41E+01
1.00E+04	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243	AM-243
	38.4%	38.1%	37.6%	36.7%	36.6%	36.6%	36.6%	36.5%	36.5%	36.5%

Table 5.25

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
7500 Years After Repository Sealing

Waste Directly Affected

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	4.87E-03 SN-126 44.0%	4.95E-03 SN-126 43.2%	4.95E-03 SN-126 43.2%	4.95E-03 SN-126 43.2%	4.95E-03 SN-126 43.2%	4.95E-03 SN-126 43.2%	4.95E-03 SN-126 43.2%	4.95E-03 SN-126 43.2%	4.95E-03 SN-126 43.2%	4.95E-03 SN-126 43.2%
2.00E+01	7.72E-03 SN-126 64.7%	9.30E-03 SN-126 53.7%	9.30E-03 SN-126 53.7%	9.30E-03 SN-126 53.7%	9.30E-03 SN-126 53.7%	9.30E-03 SN-126 53.7%	9.30E-03 SN-126 53.7%	9.30E-03 SN-126 53.7%	9.30E-03 SN-126 53.7%	9.30E-03 SN-126 53.7%
5.00E+01	2.56E-01 AM-243 55.7%	2.58E-01 AM-243 55.2%	2.60E-01 AM-243 54.7%	2.60E-01 AM-243 54.7%	2.60E-01 AM-243 54.7%	2.60E-01 AM-243 54.7%	2.60E-01 AM-243 54.7%	2.60E-01 AM-243 54.7%	2.60E-01 AM-243 54.7%	2.60E-01 AM-243 54.7%
1.00E+02	4.39E+00 AM-243 58.2%	4.39E+00 AM-243 58.2%	4.40E+00 AM-243 58.2%	4.40E+00 AM-243 58.1%	4.40E+00 AM-243 58.1%	4.40E+00 AM-243 58.1%	4.40E+00 AM-243 58.1%	4.40E+00 AM-243 58.1%	4.40E+00 AM-243 58.1%	4.40E+00 AM-243 58.1%
2.00E+02	1.01E+01 AM-243 57.9%	1.01E+01 AM-243 57.9%	1.01E+01 AM-243 57.8%	1.01E+01 AM-243 57.8%	1.01E+01 AM-243 57.8%	1.01E+01 AM-243 57.8%	1.01E+01 AM-243 57.8%	1.01E+01 AM-243 57.8%	1.01E+01 AM-243 57.8%	1.01E+01 AM-243 57.8%
5.00E+02	2.06E+01 AM-243 56.6%	2.06E+01 AM-243 56.5%	2.06E+01 AM-243 56.5%	2.06E+01 AM-243 56.5%	2.06E+01 AM-243 56.5%	2.06E+01 AM-243 56.5%	2.06E+01 AM-243 56.5%	2.06E+01 AM-243 56.5%	2.06E+01 AM-243 56.5%	2.06E+01 AM-243 56.5%
1.00E+03	2.97E+01 AM-243 54.2%	3.06E+01 AM-243 54.2%	3.06E+01 AM-243 54.2%	3.07E+01 AM-243 54.1%	3.07E+01 AM-243 54.1%	3.07E+01 AM-243 54.1%	3.07E+01 AM-243 54.1%	3.07E+01 AM-243 54.1%	3.07E+01 AM-243 54.1%	3.07E+01 AM-243 54.1%
2.00E+03	2.69E+01 AM-243 49.5%	4.11E+01 AM-243 49.3%	4.12E+01 AM-243 49.3%	4.12E+01 AM-243 49.3%	4.12E+01 AM-243 49.3%	4.12E+01 AM-243 49.3%	4.12E+01 AM-243 49.2%	4.12E+01 AM-243 49.2%	4.12E+01 AM-243 49.2%	4.12E+01 AM-243 49.2%
5.00E+03	1.69E+01 AM-243 44.6%	2.83E+01 AM-243 44.2%	3.94E+01 AM-243 43.6%	4.03E+01 AM-243 43.5%	4.03E+01 AM-243 43.5%	4.03E+01 AM-243 43.5%	4.03E+01 AM-243 43.5%	4.03E+01 AM-243 43.5%	4.03E+01 AM-243 43.5%	4.03E+01 AM-243 43.5%
1.00E+04	8.61E+00 AM-243 33.7%	1.45E+01 AM-243 33.3%	2.02E+01 PU-239 33.5%	2.66E+01 PU-239 35.5%	2.70E+01 PU-239 35.6%	2.70E+01 PU-239 35.6%	2.70E+01 PU-239 35.6%	2.70E+01 PU-239 35.6%	2.70E+01 PU-239 35.6%	2.70E+01 PU-239 35.6%

bedded salt would tend to heal itself and greatly reduce or close the pathway. Table 5.26 gives the annual dose rates at preselected times and distances for a fault into the granite tank at 1000 years. The migration of the nuclides, as well as the dominant ones, are the same in this case as they were for the direct hit case (Section 5.2.1). However, the dose rates are much higher in this case; they are the highest found among all the reference cases in this report. The highest dose rate is 340,000 rem/yr, 100 years after the event. Tables 5.27, 5.28 and 5.29 give the annual dose rates for faulting at 200, 3350, and 7500 years. For faulting at 200 years, the highest dose rate is 200,000 rem/yr, 500 years after the event; it is 110,000 rem/yr for faulting at 3350 years, and 98,000 rem/yr for faulting at 7500 years. The highest annual dose rate in the last two cases, as in the 1000-year faulting event, occurs 100 years after the event. There are no area tables associated with this scenario. The Am-241 appears at 50 years because the model treats it as uniformly distributed along the fault line. The release is integrated from 1 to 4000 meters rather than 0 to 4000 meters, in order to avoid the isolated singularity at $x = 0$. The result is a delay in dose time, the time by which the nuclide must travel the 1.0 meter distance.

5.3. Release to the Land Surface

5.3.1 Direct hit on waste

As in the release to aquifers, this release mode takes place as the result of a drilling event. A fraction (0.15 for our base case) of the waste in a canister is carried to the surface, and is subsequently dispersed into the atmosphere by resuspension (SmC 82; ADL 79). The nuclides are considered to be in an insoluble form, which gives higher lung doses. The release to the land surface is characterized by the fact that the largest dose rates always occur closest to the release (20 meters in the tables). The largest doses are always recorded at the earliest times. As dose times increase, the doses fall as the nuclide

Table 5.26

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement in GRANITE
1000 Years After Repository Sealing

Repository Water Affected

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.76E+01 SN-126 53.8%	3.90E+01 SN-126 51.8%	3.90E+01 SN-126 51.8%	3.90E+01 SN-126 51.8%	3.90E+01 SN-126 51.8%	3.90E+01 SN-126 51.8%	3.90E+01 SN-126 51.8%	3.90E+01 SN-126 51.8%	3.90E+01 SN-126 51.8%	3.90E+01 SN-126 51.8%
2.00E+01	2.53E+01 SN-126 88.0%	3.64E+01 SN-126 61.0%	3.64E+01 SN-126 61.0%	3.64E+01 SN-126 61.0%	3.64E+01 SN-126 61.0%	3.64E+01 SN-126 61.0%	3.64E+01 SN-126 61.0%	3.64E+01 SN-126 61.0%	3.64E+01 SN-126 61.0%	3.64E+01 SN-126 61.0%
5.00E+01	1.67E+05 AM-241 95.4%	1.67E+05 AM-241 95.4%	1.67E+05 AM-241 95.4%	1.67E+05 AM-241 95.4%	1.67E+05 AM-241 95.4%	1.67E+05 AM-241 95.4%	1.67E+05 AM-241 95.4%	1.67E+05 AM-241 95.4%	1.67E+05 AM-241 95.4%	1.67E+05 AM-241 95.4%
1.00E+02	3.41E+05 AM-241 95.1%	3.41E+05 AM-241 95.1%	3.41E+05 AM-241 95.1%	3.41E+05 AM-241 95.1%	3.41E+05 AM-241 95.1%	3.41E+05 AM-241 95.1%	3.41E+05 AM-241 95.1%	3.41E+05 AM-241 95.1%	3.41E+05 AM-241 95.1%	3.41E+05 AM-241 95.1%
2.00E+02	2.57E+05 AM-241 94.4%	2.57E+05 AM-241 94.4%	2.57E+05 AM-241 94.4%	2.57E+05 AM-241 94.4%	2.57E+05 AM-241 94.4%	2.57E+05 AM-241 94.4%	2.57E+05 AM-241 94.4%	2.57E+05 AM-241 94.4%	2.57E+05 AM-241 94.4%	2.57E+05 AM-241 94.4%
5.00E+02	1.75E+05 AM-241 91.6%	1.75E+05 AM-241 91.6%	1.75E+05 AM-241 91.6%	1.75E+05 AM-241 91.6%	1.75E+05 AM-241 91.6%	1.75E+05 AM-241 91.6%	1.75E+05 AM-241 91.6%	1.75E+05 AM-241 91.6%	1.75E+05 AM-241 91.6%	1.75E+05 AM-241 91.6%
1.00E+03	7.64E+04 AM-241 84.2%	1.06E+05 AM-241 84.2%	1.06E+05 AM-241 84.2%	1.06E+05 AM-241 84.2%	1.06E+05 AM-241 84.2%	1.06E+05 AM-241 84.2%	1.06E+05 AM-241 84.2%	1.06E+05 AM-241 84.2%	1.06E+05 AM-241 84.2%	1.06E+05 AM-241 84.2%
2.00E+03	2.30E+04 AM-241 55.8%	4.41E+04 AM-241 55.8%	4.41E+04 AM-241 55.8%	4.41E+04 AM-241 55.8%	4.41E+04 AM-241 55.8%	4.41E+04 AM-241 55.8%	4.41E+04 AM-241 55.8%	4.41E+04 AM-241 55.8%	4.41E+04 AM-241 55.8%	4.41E+04 AM-241 55.8%
5.00E+03	6.14E+03 AM-243 36.0%	1.13E+04 AM-243 36.0%	1.84E+04 AM-243 36.0%	2.05E+04 AM-243 36.0%	2.05E+04 AM-243 36.0%	2.05E+04 AM-243 35.9%	2.05E+04 AM-243 35.9%	2.05E+04 AM-243 35.9%	2.05E+04 AM-243 35.9%	2.05E+04 AM-243 35.9%
1.00E+04	2.60E+03 PU-239 36.8%	4.81E+03 PU-239 36.8%	7.78E+03 PU-239 36.8%	1.38E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.52E+04 PU-239 36.7%

Table 5.27

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement in GRANITE
200 Years After Repository Sealing

Repository Water Affected

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	6.57E+00 SR -90 66.3%	6.58E+00 SR -90 66.1%	6.58E+00 SR -90 66.1%	6.58E+00 SR -90 66.1%	6.58E+00 SR -90 66.1%	6.58E+00 SR -90 66.1%	6.58E+00 SR -90 66.1%	6.58E+00 SR -90 66.1%	6.58E+00 SR -90 66.1%	6.58E+00 SR -90 66.1%
2.00E+01	8.31E+00 SR -90 61.8%	1.11E+01 SR -90 63.0%	1.11E+01 SR -90 63.0%	1.11E+01 SR -90 63.0%	1.11E+01 SR -90 63.0%	1.11E+01 SR -90 63.0%	1.11E+01 SR -90 63.0%	1.11E+01 SR -90 63.0%	1.11E+01 SR -90 63.0%	1.11E+01 SR -90 63.0%
5.00E+01	9.20E+02 AM-241 97.0%	9.23E+02 AM-241 96.7%	9.26E+02 AM-241 96.4%	9.26E+02 AM-241 96.4%	9.26E+02 AM-241 96.4%	9.26E+02 AM-241 96.4%	9.26E+02 AM-241 96.4%	9.26E+02 AM-241 96.4%	9.26E+02 AM-241 96.4%	9.26E+02 AM-241 96.4%
1.00E+02	7.19E+04 AM-241 97.5%	7.19E+04 AM-241 97.5%	7.19E+04 AM-241 97.5%	7.19E+04 AM-241 97.5%	7.19E+04 AM-241 97.5%	7.19E+04 AM-241 97.5%	7.19E+04 AM-241 97.5%	7.19E+04 AM-241 97.5%	7.19E+04 AM-241 97.5%	7.19E+04 AM-241 97.5%
2.00E+02	1.54E+05 AM-241 97.2%	1.54E+05 AM-241 97.2%	1.54E+05 AM-241 97.2%	1.54E+05 AM-241 97.2%	1.54E+05 AM-241 97.2%	1.54E+05 AM-241 97.2%	1.54E+05 AM-241 97.2%	1.54E+05 AM-241 97.2%	1.54E+05 AM-241 97.2%	1.54E+05 AM-241 97.2%
5.00E+02	2.12E+05 AM-241 95.7%	2.12E+05 AM-241 95.7%	2.12E+05 AM-241 95.7%	2.12E+05 AM-241 95.7%	2.12E+05 AM-241 95.7%	2.12E+05 AM-241 95.7%	2.12E+05 AM-241 95.7%	2.12E+05 AM-241 95.7%	2.12E+05 AM-241 95.7%	2.12E+05 AM-241 95.7%
1.00E+03	1.57E+05 AM-241 91.6%	1.59E+05 AM-241 91.6%	1.59E+05 AM-241 91.6%	1.59E+05 AM-241 91.6%	1.59E+05 AM-241 91.6%	1.59E+05 AM-241 91.6%	1.59E+05 AM-241 91.6%	1.59E+05 AM-241 91.6%	1.59E+05 AM-241 91.6%	1.59E+05 AM-241 91.6%
2.00E+03	3.98E+04 AM-241 72.1%	6.50E+04 AM-241 72.1%	6.50E+04 AM-241 72.1%	6.50E+04 AM-241 72.1%	6.51E+04 AM-241 72.1%	6.51E+04 AM-241 72.1%	6.51E+04 AM-241 72.1%	6.51E+04 AM-241 72.1%	6.51E+04 AM-241 72.1%	6.51E+04 AM-241 72.1%
5.00E+03	6.81E+03 AM-243 35.7%	1.26E+04 AM-243 35.7%	2.03E+04 AM-243 35.7%	2.10E+04 AM-243 35.7%	2.10E+04 AM-243 35.7%	2.11E+04 AM-243 35.7%	2.11E+04 AM-243 35.7%	2.11E+04 AM-243 35.7%	2.11E+04 AM-243 35.7%	2.11E+04 AM-243 35.6%
1.00E+04	2.83E+03 PU-239 36.1%	5.22E+03 PU-239 36.1%	8.45E+03 PU-239 36.1%	1.50E+04 PU-239 36.1%	1.57E+04 PU-239 36.1%	1.57E+04 PU-239 36.1%	1.57E+04 PU-239 36.1%	1.57E+04 PU-239 36.1%	1.58E+04 PU-239 36.1%	1.58E+04 PU-239 36.1%

Table 5.28

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement in GRANITE
3350 Years After Repository Sealing

Repository Water Affected

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.83E+02 SN-126 54.9%	1.90E+02 SN-126 53.0%	1.90E+02 SN-126 53.0%	1.90E+02 SN-126 53.0%	1.90E+02 SN-126 53.0%	1.90E+02 SN-126 53.0%	1.90E+02 SN-126 53.0%	1.90E+02 SN-126 53.0%	1.90E+02 SN-126 53.0%	1.90E+02 SN-126 53.0%
2.00E+01	1.22E+02 SN-126 89.5%	1.75E+02 SN-126 62.2%	1.75E+02 SN-126 62.2%	1.75E+02 SN-126 62.2%	1.75E+02 SN-126 62.2%	1.75E+02 SN-126 62.2%	1.75E+02 SN-126 62.2%	1.75E+02 SN-126 62.2%	1.75E+02 SN-126 62.2%	1.75E+02 SN-126 62.2%
5.00E+01	5.57E+04 AM-241 41.5%	5.57E+04 AM-241 41.5%	5.58E+04 AM-241 41.5%	5.58E+04 AM-241 41.4%	5.58E+04 AM-241 41.4%	5.58E+04 AM-241 41.4%	5.58E+04 AM-241 41.4%	5.58E+04 AM-241 41.4%	5.58E+04 AM-241 41.4%	5.58E+04 AM-241 41.4%
1.00E+02	1.09E+05 AM-241 39.8%	1.09E+05 AM-241 39.8%	1.09E+05 AM-241 39.8%	1.09E+05 AM-241 39.8%	1.09E+05 AM-241 39.8%	1.09E+05 AM-241 39.8%	1.09E+05 AM-241 39.8%	1.09E+05 AM-241 39.8%	1.09E+05 AM-241 39.8%	1.09E+05 AM-241 39.8%
2.00E+02	7.41E+04 AM-241 36.4%	7.42E+04 AM-241 36.4%	7.42E+04 AM-241 36.4%	7.42E+04 AM-241 36.4%	7.42E+04 AM-241 36.4%	7.42E+04 AM-241 36.4%	7.42E+04 AM-241 36.4%	7.42E+04 AM-241 36.4%	7.42E+04 AM-241 36.4%	7.42E+04 AM-241 36.4%
5.00E+02	4.50E+04 AM-243 27.7%	4.50E+04 AM-243 27.7%	4.50E+04 AM-243 27.7%	4.51E+04 AM-243 27.7%	4.51E+04 AM-243 27.7%	4.51E+04 AM-243 27.7%	4.51E+04 AM-243 27.7%	4.51E+04 AM-243 27.7%	4.51E+04 AM-243 27.7%	4.51E+04 AM-243 27.7%
1.00E+03	9.48E+03 AM-243 31.9%	3.18E+04 AM-243 31.9%	3.18E+04 AM-243 31.9%	3.18E+04 AM-243 31.9%	3.18E+04 AM-243 31.9%	3.18E+04 AM-243 31.9%	3.18E+04 AM-243 31.9%	3.18E+04 AM-243 31.9%	3.18E+04 AM-243 31.9%	3.18E+04 AM-243 31.9%
2.00E+03	7.04E+03 AM-243 35.5%	2.43E+04 AM-243 35.5%	2.43E+04 AM-243 35.5%	2.43E+04 AM-243 35.5%	2.43E+04 AM-243 35.5%	2.43E+04 AM-243 35.5%	2.43E+04 AM-243 35.5%	2.43E+04 AM-243 35.5%	2.43E+04 AM-243 35.5%	2.43E+04 AM-243 35.5%
5.00E+03	4.05E+03 AM-243 34.8%	7.48E+03 AM-243 34.8%	1.21E+04 AM-243 34.8%	1.88E+04 AM-243 34.8%	1.88E+04 AM-243 34.8%	1.88E+04 AM-243 34.8%	1.88E+04 AM-243 34.8%	1.88E+04 AM-243 34.8%	1.88E+04 AM-243 34.8%	1.88E+04 AM-243 34.8%
1.00E+04	1.77E+03 PU-239 39.9%	3.27E+03 PU-239 39.9%	5.30E+03 PU-239 39.9%	9.43E+03 PU-239 39.9%	1.30E+04 PU-239 39.9%	1.30E+04 PU-239 39.9%	1.30E+04 PU-239 39.9%	1.30E+04 PU-239 39.9%	1.30E+04 PU-239 39.9%	1.30E+04 PU-239 39.9%

Table 5.29

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement in GRANITE
7500 Years After Repository Sealing

Repository Water Affected

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.55E+02 SN-126 56.0%	3.67E+02 SN-126 54.0%	3.67E+02 SN-126 54.0%	3.67E+02 SN-126 54.0%	3.67E+02 SN-126 54.0%	3.67E+02 SN-126 54.0%	3.67E+02 SN-126 54.0%	3.67E+02 SN-126 54.0%	3.67E+02 SN-126 54.0%	3.67E+02 SN-126 54.0%
2.00E+01	2.38E+02 SN-126 90.0%	3.39E+02 SN-126 63.2%	3.39E+02 SN-126 63.2%	3.39E+02 SN-126 63.2%	3.39E+02 SN-126 63.2%	3.39E+02 SN-126 63.2%	3.39E+02 SN-126 63.2%	3.39E+02 SN-126 63.2%	3.39E+02 SN-126 63.2%	3.39E+02 SN-126 63.2%
5.00E+01	4.92E+04 AM-243 35.3%	4.92E+04 AM-243 35.3%	4.93E+04 AM-243 35.3%	4.93E+04 AM-243 35.2%	4.93E+04 AM-243 35.2%	4.93E+04 AM-243 35.2%	4.93E+04 AM-243 35.2%	4.93E+04 AM-243 35.2%	4.93E+04 AM-243 35.2%	4.93E+04 AM-243 35.2%
1.00E+02	9.77E+04 AM-243 35.3%	9.77E+04 AM-243 35.3%	9.77E+04 AM-243 35.3%	9.77E+04 AM-243 35.3%	9.78E+04 AM-243 35.3%	9.78E+04 AM-243 35.3%	9.78E+04 AM-243 35.3%	9.78E+04 AM-243 35.3%	9.78E+04 AM-243 35.3%	9.78E+04 AM-243 35.3%
2.00E+02	6.85E+04 AM-243 35.3%	6.86E+04 AM-243 35.2%	6.86E+04 AM-243 35.2%	6.86E+04 AM-243 35.2%	6.86E+04 AM-243 35.2%	6.86E+04 AM-243 35.2%	6.86E+04 AM-243 35.2%	6.86E+04 AM-243 35.2%	6.86E+04 AM-243 35.2%	6.86E+04 AM-243 35.2%
5.00E+02	4.40E+04 AM-243 35.1%	4.40E+04 AM-243 35.1%	4.40E+04 AM-243 35.1%	4.40E+04 AM-243 35.0%	4.40E+04 AM-243 35.0%	4.40E+04 AM-243 35.0%	4.40E+04 AM-243 35.0%	4.40E+04 AM-243 35.0%	4.40E+04 AM-243 35.0%	4.40E+04 AM-243 35.0%
1.00E+03	3.95E+03 AM-243 34.7%	3.22E+04 AM-243 34.7%	3.22E+04 AM-243 34.7%	3.22E+04 AM-243 34.7%	3.22E+04 AM-243 34.7%	3.22E+04 AM-243 34.7%	3.22E+04 AM-243 34.7%	3.22E+04 AM-243 34.7%	3.22E+04 AM-243 34.7%	3.23E+04 AM-243 34.7%
2.00E+03	3.34E+03 PU-239 34.8%	2.40E+04 PU-239 34.8%	2.40E+04 PU-239 34.8%	2.40E+04 PU-239 34.8%	2.41E+04 PU-239 34.8%	2.41E+04 PU-239 34.8%	2.41E+04 PU-239 34.8%	2.41E+04 PU-239 34.8%	2.41E+04 PU-239 34.8%	2.41E+04 PU-239 34.8%
5.00E+03	2.04E+03 PU-239 38.8%	3.76E+03 PU-239 38.8%	6.08E+03 PU-239 38.8%	1.59E+04 PU-239 38.8%	1.59E+04 PU-239 38.8%	1.59E+04 PU-239 38.8%	1.59E+04 PU-239 38.8%	1.59E+04 PU-239 38.7%	1.59E+04 PU-239 38.7%	1.59E+04 PU-239 38.7%
1.00E+04	9.15E+02 PU-239 45.2%	1.69E+03 PU-239 45.2%	2.74E+03 PU-239 45.2%	4.87E+03 PU-239 45.2%	1.01E+04 PU-239 45.3%	1.01E+04 PU-239 45.2%	1.01E+04 PU-239 45.2%	1.01E+04 PU-239 45.2%	1.01E+04 PU-239 45.2%	1.01E+04 PU-239 45.2%

is removed by decay, soil penetration, and secondary resuspension. Dose rates from later releases are lower than those from earlier releases because of more radionuclide decay before the event.

We can estimate the contaminated areas by noticing that the concentration equations are independent of direction. To ascertain the area contaminated above a given value, the code interpolates to find the distance at which that dose is incurred, and finds the area of a circle lith the distance as the radius. This gives a picture of the land surface contaminated above a selected level.

In the 1000-year event, Table 5.2 shows Am-241 as the dominant radionuclide for the first 500 years. The longer-lived Pu-239 and -240 dominate the rest of the table. Doses are moderate, the highest being 11 rem/yr at 20 meters and 10 years, and decrease rapidly with distance and slowly with time. The 200-year event (Table 5.30) is dominated by Am-241 for 500 years, then by Pu-239 and -240. The 3350-year and 7500-year events (Tables 5.31 and 5.32) are dominated by Pu-239 and Pu-240. As the total time increases the dose rates and areas contaminated decrease due primarily to radiological decay.

Table 5.33 shows the areas contaminated above specified dose levels. For early drilling, at 200 and 1000 years after repository sealing, more than 10 ha are contaminated enough to give dose rates above 0.5 rem/yr for fairly long periods of time. Smaller areas are contaminated enough to give dose rates of 5 rem/yr. For later drilling, at 3350 and 7500 years after sealing, less than three ha are contaminated enough to give dose rates above 0.5 rem/yr and none are contaminated enough to give 5 rem/yr.

5.3.2 Brine pocket

Tables 5.34 through 5.37 give the annual dose rates resulting from releases of waste to the land surface by drilling into a brine pocket. The annual dose rates for this release scenario are much smaller than those from the direct hit case discussed in the previous section. The largest dose rate calculated is only 0.02 rem/yr, 90% from Am-241.

Table 5.30

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling
200 Years After Repository Sealing

Drill Hits Waste

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.88E+01 AM-241 70.7%	7.61E+00 AM-241 70.7%	2.76E+00 AM-241 70.7%	9.87E-01 AM-241 70.7%	2.47E-01 AM-241 70.7%	1.32E-01 AM-241 70.7%	8.37E-02 AM-241 70.7%	4.36E-02 AM-241 70.7%	2.72E-02 AM-241 70.7%	8.27E-03 AM-241 70.7%
2.00E+01	2.81E+01 AM-241 71.0%	7.42E+00 AM-241 71.0%	2.69E+00 AM-241 71.0%	9.63E-01 AM-241 71.0%	2.41E-01 AM-241 71.0%	1.29E-01 AM-241 71.0%	8.17E-02 AM-241 71.0%	4.26E-02 AM-241 71.0%	2.65E-02 AM-241 71.0%	8.08E-03 AM-241 71.0%
5.00E+01	2.62E+01 AM-241 71.7%	6.92E+00 AM-241 71.7%	2.51E+00 AM-241 71.7%	8.98E-01 AM-241 71.7%	2.25E-01 AM-241 71.7%	1.20E-01 AM-241 71.7%	7.62E-02 AM-241 71.7%	3.97E-02 AM-241 71.7%	2.47E-02 AM-241 71.7%	7.53E-03 AM-241 71.7%
1.00E+02	2.35E+01 AM-241 72.2%	6.21E+00 AM-241 72.2%	2.25E+00 AM-241 72.2%	8.06E-01 AM-241 72.2%	2.02E-01 AM-241 72.2%	1.08E-01 AM-241 72.2%	6.84E-02 AM-241 72.2%	3.56E-02 AM-241 72.2%	2.22E-02 AM-241 72.2%	6.76E-03 AM-241 72.2%
2.00E+02	1.93E+01 AM-241 71.8%	5.11E+00 AM-241 71.8%	1.85E+00 AM-241 71.8%	6.63E-01 AM-241 71.8%	1.66E-01 AM-241 71.8%	8.84E-02 AM-241 71.8%	5.62E-02 AM-241 71.8%	2.93E-02 AM-241 71.8%	1.83E-02 AM-241 71.8%	5.56E-03 AM-241 71.8%
5.00E+02	1.17E+01 AM-241 64.7%	3.09E+00 AM-241 64.7%	1.12E+00 AM-241 64.7%	4.01E-01 AM-241 64.7%	1.00E-01 AM-241 64.7%	5.35E-02 AM-241 64.7%	3.40E-02 AM-241 64.7%	1.77E-02 AM-241 64.7%	1.11E-02 AM-241 64.7%	3.36E-03 AM-241 64.7%
1.00E+03	5.82E+00 AM-241 47.4%	1.54E+00 AM-241 47.4%	5.57E-01 AM-241 47.4%	1.99E-01 AM-241 47.4%	4.99E-02 AM-241 47.4%	2.66E-02 AM-241 47.4%	1.69E-02 AM-241 47.4%	8.82E-03 AM-241 47.4%	5.50E-03 AM-241 47.4%	1.67E-03 AM-241 47.4%
2.00E+03	2.09E+00 PU-240 44.9%	5.51E-01 PU-240 44.9%	2.00E-01 PU-240 44.9%	7.15E-02 PU-240 44.9%	1.79E-02 PU-240 44.9%	9.54E-03 PU-240 44.9%	6.07E-03 PU-240 44.9%	3.16E-03 PU-240 44.9%	1.97E-03 PU-240 44.9%	6.00E-04 PU-240 44.9%
5.00E+03	3.09E-01 PU-240 49.1%	8.16E-02 PU-240 49.1%	2.96E-02 PU-240 49.1%	1.06E-02 PU-240 49.1%	2.65E-03 PU-240 49.1%	1.41E-03 PU-240 49.1%	8.98E-04 PU-240 49.1%	4.68E-04 PU-240 49.1%	2.92E-04 PU-240 49.1%	8.87E-05 PU-240 49.1%
1.00E+04	1.80E-02 PU-239 57.6%	4.76E-03 PU-239 57.6%	1.72E-03 PU-239 57.6%	6.17E-04 PU-239 57.6%	1.54E-04 PU-239 57.6%	8.23E-05 PU-239 57.6%	5.23E-05 PU-239 57.6%	2.73E-05 PU-239 57.6%	1.70E-05 PU-239 57.6%	5.17E-06 PU-239 57.6%

Table 5.31

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling
3350 Years After Repository Sealing

Drill Hits Waste

DISTANCE (meters)

TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	4.51E+00 PU-240 50.4%	1.19E+00 PU-240 50.4%	4.32E-01 PU-240 50.4%	1.55E-01 PU-240 50.4%	3.87E-02 PU-240 50.4%	2.06E-02 PU-240 50.4%	1.31E-02 PU-240 50.4%	6.84E-03 PU-240 50.4%	4.26E-03 PU-240 50.4%	1.30E-03 PU-240 50.4%
2.00E+01	4.48E+00 PU-240 50.4%	1.18E+00 PU-240 50.4%	4.29E-01 PU-240 50.4%	1.54E-01 PU-240 50.4%	3.84E-02 PU-240 50.4%	2.05E-02 PU-240 50.4%	1.30E-02 PU-240 50.4%	6.79E-03 PU-240 50.4%	4.23E-03 PU-240 50.4%	1.29E-03 PU-240 50.4%
5.00E+01	4.39E+00 PU-240 50.5%	1.16E+00 PU-240 50.5%	4.21E-01 PU-240 50.5%	1.51E-01 PU-240 50.5%	3.77E-02 PU-240 50.5%	2.01E-02 PU-240 50.5%	1.28E-02 PU-240 50.5%	6.66E-03 PU-240 50.5%	4.15E-03 PU-240 50.5%	1.26E-03 PU-240 50.5%
1.00E+02	4.26E+00 PU-240 50.5%	1.13E+00 PU-240 50.5%	4.08E-01 PU-240 50.5%	1.46E-01 PU-240 50.5%	3.65E-02 PU-240 50.5%	1.95E-02 PU-240 50.5%	1.24E-02 PU-240 50.5%	6.46E-03 PU-240 50.5%	4.02E-03 PU-240 50.5%	1.22E-03 PU-240 50.5%
2.00E+02	4.00E+00 PU-240 50.6%	1.06E+00 PU-240 50.6%	3.83E-01 PU-240 50.6%	1.37E-01 PU-240 50.6%	3.43E-02 PU-240 50.6%	1.83E-02 PU-240 50.6%	1.16E-02 PU-240 50.6%	6.07E-03 PU-240 50.6%	3.78E-03 PU-240 50.6%	1.15E-03 PU-240 50.6%
5.00E+02	3.33E+00 PU-240 50.6%	8.81E-01 PU-240 50.6%	3.19E-01 PU-240 50.6%	1.14E-01 PU-240 50.6%	2.86E-02 PU-240 50.6%	1.53E-02 PU-240 50.6%	9.70E-03 PU-240 50.6%	5.06E-03 PU-240 50.6%	3.15E-03 PU-240 50.6%	9.59E-04 PU-240 50.6%
1.00E+03	2.48E+00 PU-240 50.2%	6.55E-01 PU-240 50.2%	2.37E-01 PU-240 50.2%	8.50E-02 PU-240 50.2%	2.13E-02 PU-240 50.2%	1.13E-02 PU-240 50.2%	7.21E-03 PU-240 50.2%	3.76E-03 PU-240 50.2%	2.34E-03 PU-240 50.2%	7.13E-04 PU-240 50.2%
2.00E+03	1.39E+00 PU-240 48.8%	3.67E-01 PU-240 48.8%	1.33E-01 PU-240 48.8%	4.76E-02 PU-240 48.8%	1.19E-02 PU-240 48.8%	6.36E-03 PU-240 48.8%	4.04E-03 PU-240 48.8%	2.11E-03 PU-240 48.8%	1.31E-03 PU-240 48.8%	4.00E-04 PU-240 48.8%
5.00E+03	2.52E-01 PU-239 54.3%	6.65E-02 PU-239 54.3%	2.41E-02 PU-239 54.3%	8.62E-03 PU-239 54.3%	2.16E-03 PU-239 54.3%	1.15E-03 PU-239 54.3%	7.31E-04 PU-239 54.3%	3.81E-04 PU-239 54.3%	2.38E-04 PU-239 54.3%	7.23E-05 PU-239 54.3%
1.00E+04	1.50E-02 PU-239 63.0%	3.97E-03 PU-239 63.0%	1.44E-03 PU-239 63.0%	5.15E-04 PU-239 63.0%	1.29E-04 PU-239 63.0%	6.87E-05 PU-239 63.0%	4.37E-05 PU-239 63.0%	2.28E-05 PU-239 63.0%	1.42E-05 PU-239 63.0%	4.32E-06 PU-239 63.0%

Table 5.32

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling
7500 Years After Repository Sealing

Drill Hits Waste

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.30E+00 PU-239 52.7%	8.72E-01 PU-239 52.7%	3.16E-01 PU-239 52.7%	1.13E-01 PU-239 52.7%	2.83E-02 PU-239 52.7%	1.51E-02 PU-239 52.7%	9.60E-03 PU-239 52.7%	5.00E-03 PU-239 52.7%	3.12E-03 PU-239 52.7%	9.49E-04 PU-239 52.7%
2.00E+01	3.28E+00 PU-239 52.8%	8.67E-01 PU-239 52.8%	3.14E-01 PU-239 52.8%	1.12E-01 PU-239 52.8%	2.81E-02 PU-239 52.8%	1.50E-02 PU-239 52.8%	9.54E-03 PU-239 52.8%	4.97E-03 PU-239 52.8%	3.10E-03 PU-239 52.8%	9.43E-04 PU-239 52.8%
5.00E+01	3.22E+00 PU-239 52.9%	8.51E-01 PU-239 52.9%	3.08E-01 PU-239 52.9%	1.10E-01 PU-239 52.9%	2.76E-02 PU-239 52.9%	1.47E-02 PU-239 52.9%	9.37E-03 PU-239 52.9%	4.88E-03 PU-239 52.9%	3.04E-03 PU-239 52.9%	9.26E-04 PU-239 52.9%
1.00E+02	3.13E+00 PU-239 53.0%	8.27E-01 PU-239 53.0%	3.00E-01 PU-239 53.0%	1.07E-01 PU-239 53.0%	2.68E-02 PU-239 53.0%	1.43E-02 PU-239 53.0%	9.10E-03 PU-239 53.0%	4.75E-03 PU-239 53.0%	2.96E-03 PU-239 53.0%	9.00E-04 PU-239 53.0%
2.00E+02	2.96E+00 PU-239 53.2%	7.82E-01 PU-239 53.2%	2.83E-01 PU-239 53.2%	1.01E-01 PU-239 53.2%	2.54E-02 PU-239 53.2%	1.35E-02 PU-239 53.2%	8.60E-03 PU-239 53.2%	4.48E-03 PU-239 53.2%	2.79E-03 PU-239 53.2%	8.50E-04 PU-239 53.2%
5.00E+02	2.49E+00 PU-239 53.7%	6.59E-01 PU-239 53.7%	2.39E-01 PU-239 53.7%	8.55E-02 PU-239 53.7%	2.14E-02 PU-239 53.7%	1.14E-02 PU-239 53.7%	7.25E-03 PU-239 53.7%	3.78E-03 PU-239 53.7%	2.36E-03 PU-239 53.7%	7.17E-04 PU-239 53.7%
1.00E+03	1.88E+00 PU-239 54.6%	4.96E-01 PU-239 54.6%	1.80E-01 PU-239 54.6%	6.44E-02 PU-239 54.6%	1.61E-02 PU-239 54.6%	8.59E-03 PU-239 54.6%	5.46E-03 PU-239 54.6%	2.85E-03 PU-239 54.6%	1.77E-03 PU-239 54.6%	5.40E-04 PU-239 54.6%
2.00E+03	1.07E+00 PU-239 56.4%	2.82E-01 PU-239 56.4%	1.02E-01 PU-239 56.4%	3.66E-02 PU-239 56.4%	9.14E-03 PU-239 56.4%	4.88E-03 PU-239 56.4%	3.10E-03 PU-239 56.4%	1.62E-03 PU-239 56.4%	1.01E-03 PU-239 56.4%	3.07E-04 PU-239 56.4%
5.00E+03	1.97E-01 PU-239 61.6%	5.20E-02 PU-239 61.6%	1.88E-02 PU-239 61.6%	6.74E-03 PU-239 61.6%	1.69E-03 PU-239 61.6%	9.00E-04 PU-239 61.6%	5.72E-04 PU-239 61.6%	2.98E-04 PU-239 61.6%	1.86E-04 PU-239 61.6%	5.65E-05 PU-239 61.6%
1.00E+04	1.20E-02 PU-239 69.7%	3.18E-03 PU-239 69.7%	1.15E-03 PU-239 69.7%	4.13E-04 PU-239 69.7%	1.03E-04 PU-239 69.7%	5.51E-05 PU-239 69.7%	3.50E-05 PU-239 69.7%	1.83E-05 PU-239 69.7%	1.14E-05 PU-239 69.7%	3.46E-06 PU-239 69.7%

Table 5.33

Area (ha*) of the Land Surface Contaminated Above the Specified Dose Rate Levels Following a Direct Drilling Hit on Waste

Time After Drill (yr)	200 years after sealing: Dose Level (rem/yr) 0.5	5	50	500	1000 years after sealing: Dose Level (rem/yr) 0.5	5	50	500
10	50	1.8	0	0	11	0.6	0	0
20	49	1.8	0	0	10	0.6	0	0
50	45	1.6	0	0	10	0.5	0	0
100	39	1.4	0	0	10	0.5	0	0
200	28	0.8	0	0	8.3	0.4	0	0
500	11	0.6	0	0	4.8	0.2	0	0
1,000	4.2	0.2	0	0	2.5	0	0	0
2,000	1.0	0	0	0	0.8	0	0	0
5,000	0	0	0	0	0	0	0	0
10,000	0	0	0	0	0	0	0	0
	3350 years after sealing				7500 years after sealing			
10	2.6	0	0	0	1.7	0	0	0
20	2.5	0	0	0	1.6	0	0	0
50	2.5	0	0	0	1.6	0	0	0
100	2.4	0	0	0	1.5	0	0	0
200	2.2	0	0	0	1.4	0	0	0
500	1.7	0	0	0	1.2	0	0	0
1,000	1.1	0	0	0	0.8	0	0	0
2,000	0.5	0	0	0	0.4	0	0	0
5,000	0	0	0	0	0	0	0	0
10,000	0	0	0	0	0	0	0	0

*1 hectare (ha) = 10^4 square meters

Table 5.34

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.74E-02 AM-241 90.5%	4.59E-03 AM-241 90.5%	1.66E-03 AM-241 90.5%	5.95E-04 AM-241 90.5%	1.49E-04 AM-241 90.5%	7.95E-05 AM-241 90.5%	5.05E-05 AM-241 90.5%	2.63E-05 AM-241 90.5%	1.64E-05 AM-241 90.5%	4.99E-06 AM-241 90.5%
2.00E+01	1.70E-02 AM-241 90.6%	4.49E-03 AM-241 90.6%	1.63E-03 AM-241 90.6%	5.83E-04 AM-241 90.6%	1.46E-04 AM-241 90.6%	7.78E-05 AM-241 90.6%	4.94E-05 AM-241 90.6%	2.58E-05 AM-241 90.6%	1.61E-05 AM-241 90.6%	4.89E-06 AM-241 90.6%
5.00E+01	1.59E-02 AM-241 91.0%	4.21E-03 AM-241 91.0%	1.53E-03 AM-241 91.0%	5.46E-04 AM-241 91.0%	1.37E-04 AM-241 91.0%	7.29E-05 AM-241 91.0%	4.63E-05 AM-241 91.0%	2.42E-05 AM-241 91.0%	1.50E-05 AM-241 91.0%	4.58E-06 AM-241 91.0%
1.00E+02	1.43E-02 AM-241 91.3%	3.79E-03 AM-241 91.3%	1.37E-03 AM-241 91.3%	4.92E-04 AM-241 91.3%	1.23E-04 AM-241 91.3%	6.56E-05 AM-241 91.3%	4.17E-05 AM-241 91.3%	2.18E-05 AM-241 91.3%	1.36E-05 AM-241 91.3%	4.12E-06 AM-241 91.3%
2.00E+02	1.17E-02 AM-241 91.4%	3.10E-03 AM-241 91.4%	1.12E-03 AM-241 91.4%	4.02E-04 AM-241 91.4%	1.00E-04 AM-241 91.4%	5.36E-05 AM-241 91.4%	3.41E-05 AM-241 91.4%	1.78E-05 AM-241 91.4%	1.11E-05 AM-241 91.4%	3.37E-06 AM-241 91.4%
5.00E+02	6.58E-03 AM-241 88.9%	1.74E-03 AM-241 88.9%	6.30E-04 AM-241 88.9%	2.26E-04 AM-241 88.9%	5.64E-05 AM-241 88.9%	3.01E-05 AM-241 88.9%	1.91E-05 AM-241 88.9%	9.97E-06 AM-241 88.9%	6.21E-06 AM-241 88.9%	1.89E-06 AM-241 88.9%
1.00E+03	2.67E-03 AM-241 79.9%	7.05E-04 AM-241 79.9%	2.55E-04 AM-241 79.9%	9.14E-05 AM-241 79.9%	2.29E-05 AM-241 79.9%	1.22E-05 AM-241 79.9%	7.76E-06 AM-241 79.9%	4.04E-06 AM-241 79.9%	2.52E-06 AM-241 79.9%	7.67E-07 AM-241 79.9%
2.00E+03	5.78E-04 AM-243 51.0%	1.53E-04 AM-243 51.0%	5.54E-05 AM-243 51.0%	1.98E-05 AM-243 51.0%	4.96E-06 AM-243 51.0%	2.65E-06 AM-243 51.0%	1.68E-06 AM-243 51.0%	8.77E-07 AM-243 51.0%	5.46E-07 AM-243 51.0%	1.66E-07 AM-243 51.0%
5.00E+03	5.01E-05 AM-243 98.7%	1.32E-05 AM-243 98.7%	4.80E-06 AM-243 98.7%	1.72E-06 AM-243 98.7%	4.29E-07 AM-243 98.7%	2.29E-07 AM-243 98.7%	1.46E-07 AM-243 98.7%	7.59E-08 AM-243 98.7%	4.73E-08 AM-243 98.7%	1.44E-08 AM-243 98.7%
1.00E+04	2.52E-06 AM-243 100.0%	6.65E-07 AM-243 100.0%	2.41E-07 AM-243 100.0%	8.62E-08 AM-243 100.0%	2.16E-08 AM-243 100.0%	1.15E-08 AM-243 100.0%	7.32E-09 AM-243 100.0%	3.81E-09 AM-243 100.0%	2.38E-09 AM-243 100.0%	7.23E-10 AM-243 100.0%

Table 5.35

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
200 Years After Repository Sealing

Drill Hits Repository Water

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	5.71E-02 PU-238 70.7%	1.51E-02 PU-238 70.7%	5.47E-03 PU-238 70.7%	1.96E-03 PU-238 70.7%	4.90E-04 PU-238 70.7%	2.61E-04 PU-238 70.7%	1.66E-04 PU-238 70.7%	8.66E-05 PU-238 70.7%	5.40E-05 PU-238 70.7%	1.64E-05 PU-238 70.7%
2.00E+01	5.36E-02 PU-238 69.4%	1.42E-02 PU-238 69.4%	5.13E-03 PU-238 69.4%	1.84E-03 PU-238 69.3%	4.60E-04 PU-238 69.4%	2.45E-04 PU-238 69.4%	1.56E-04 PU-238 69.3%	8.13E-05 PU-238 69.3%	5.06E-05 PU-238 69.4%	1.54E-05 PU-238 69.4%
5.00E+01	4.45E-02 PU-238 65.2%	1.17E-02 PU-238 65.2%	4.26E-03 PU-238 65.2%	1.52E-03 PU-238 65.2%	3.81E-04 PU-238 65.2%	2.03E-04 PU-238 65.2%	1.29E-04 PU-238 65.2%	6.74E-05 PU-238 65.2%	4.20E-05 PU-238 65.2%	1.28E-05 PU-238 65.2%
1.00E+02	3.32E-02 PU-238 57.7%	8.77E-03 PU-238 57.7%	3.18E-03 PU-238 57.7%	1.14E-03 PU-238 57.7%	2.84E-04 PU-238 57.7%	1.52E-04 PU-238 57.7%	9.65E-05 PU-238 57.7%	5.03E-05 PU-238 57.7%	3.13E-05 PU-238 57.7%	9.54E-06 PU-238 57.7%
2.00E+02	1.99E-02 AM-241 53.7%	5.27E-03 AM-241 53.7%	1.91E-03 AM-241 53.7%	6.83E-04 AM-241 53.7%	1.71E-04 AM-241 53.7%	9.12E-05 AM-241 53.7%	5.80E-05 AM-241 53.7%	3.02E-05 AM-241 53.7%	1.88E-05 AM-241 53.7%	5.73E-06 AM-241 53.7%
5.00E+02	7.26E-03 AM-241 80.5%	1.92E-03 AM-241 80.5%	6.95E-04 AM-241 80.5%	2.49E-04 AM-241 80.5%	6.23E-05 AM-241 80.5%	3.32E-05 AM-241 80.5%	2.11E-05 AM-241 80.5%	1.10E-05 AM-241 80.5%	6.86E-06 AM-241 80.5%	2.09E-06 AM-241 80.5%
1.00E+03	2.68E-03 AM-241 79.6%	7.08E-04 AM-241 79.6%	2.56E-04 AM-241 79.6%	9.18E-05 AM-241 79.6%	2.30E-05 AM-241 79.6%	1.23E-05 AM-241 79.6%	7.79E-06 AM-241 79.6%	4.06E-06 AM-241 79.6%	2.53E-06 AM-241 79.6%	7.70E-07 AM-241 79.6%
2.00E+03	5.78E-04 AM-243 51.0%	1.53E-04 AM-243 51.0%	5.54E-05 AM-243 51.0%	1.98E-05 AM-243 51.0%	4.96E-06 AM-243 51.0%	2.65E-06 AM-243 51.0%	1.68E-06 AM-243 51.0%	8.77E-07 AM-243 51.0%	5.46E-07 AM-243 51.0%	1.66E-07 AM-243 51.0%
5.00E+03	5.01E-05 AM-243 98.7%	1.32E-05 AM-243 98.7%	4.80E-06 AM-243 98.7%	1.72E-06 AM-243 98.7%	4.29E-07 AM-243 98.7%	2.29E-07 AM-243 98.7%	1.46E-07 AM-243 98.7%	7.59E-08 AM-243 98.7%	4.73E-08 AM-243 98.7%	1.44E-08 AM-243 98.7%
1.00E+04	2.52E-06 AM-243 100.0%	6.65E-07 AM-243 100.0%	2.41E-07 AM-243 100.0%	8.62E-08 AM-243 100.0%	2.16E-08 AM-243 100.0%	1.15E-08 AM-243 100.0%	7.32E-09 AM-243 100.0%	3.81E-09 AM-243 100.0%	2.38E-09 AM-243 100.0%	7.23E-10 AM-243 100.0%

Table 5.36

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
3350 Years After Repository Sealing

Drill Hits Repository Water

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.67E-02 AM-241 94.2%	4.41E-03 AM-241 94.2%	1.60E-03 AM-241 94.2%	5.72E-04 AM-241 94.2%	1.43E-04 AM-241 94.2%	7.63E-05 AM-241 94.2%	4.85E-05 AM-241 94.2%	2.53E-05 AM-241 94.2%	1.58E-05 AM-241 94.2%	4.80E-06 AM-241 94.2%
2.00E+01	1.64E-02 AM-241 94.1%	4.32E-03 AM-241 94.1%	1.57E-03 AM-241 94.1%	5.61E-04 AM-241 94.1%	1.40E-04 AM-241 94.1%	7.49E-05 AM-241 94.1%	4.76E-05 AM-241 94.1%	2.48E-05 AM-241 94.1%	1.55E-05 AM-241 94.1%	4.70E-06 AM-241 94.1%
5.00E+01	1.54E-02 AM-241 93.9%	4.08E-03 AM-241 93.9%	1.48E-03 AM-241 93.9%	5.29E-04 AM-241 93.9%	1.32E-04 AM-241 93.9%	7.06E-05 AM-241 93.9%	4.49E-05 AM-241 93.9%	2.34E-05 AM-241 93.9%	1.46E-05 AM-241 93.9%	4.44E-06 AM-241 93.9%
1.00E+02	1.40E-02 AM-241 93.5%	3.71E-03 AM-241 93.5%	1.34E-03 AM-241 93.5%	4.81E-04 AM-241 93.5%	1.20E-04 AM-241 93.5%	6.41E-05 AM-241 93.5%	4.08E-05 AM-241 93.5%	2.13E-05 AM-241 93.5%	1.32E-05 AM-241 93.5%	4.03E-06 AM-241 93.5%
2.00E+02	1.16E-02 AM-241 92.6%	3.06E-03 AM-241 92.6%	1.11E-03 AM-241 92.6%	3.97E-04 AM-241 92.6%	9.92E-05 AM-241 92.6%	5.29E-05 AM-241 92.6%	3.37E-05 AM-241 92.6%	1.75E-05 AM-241 92.6%	1.09E-05 AM-241 92.6%	3.33E-06 AM-241 92.6%
5.00E+02	6.57E-03 AM-241 89.0%	1.74E-03 AM-241 89.0%	6.29E-04 AM-241 89.0%	2.25E-04 AM-241 89.0%	5.63E-05 AM-241 89.0%	3.00E-05 AM-241 89.0%	1.91E-05 AM-241 89.0%	9.96E-06 AM-241 89.0%	6.20E-06 AM-241 89.0%	1.89E-06 AM-241 89.0%
1.00E+03	2.67E-03 AM-241 79.9%	7.05E-04 AM-241 79.9%	2.55E-04 AM-241 79.9%	9.14E-05 AM-241 79.9%	2.29E-05 AM-241 79.9%	1.22E-05 AM-241 79.9%	7.76E-06 AM-241 79.9%	4.04E-06 AM-241 79.9%	2.52E-06 AM-241 79.9%	7.67E-07 AM-241 79.9%
2.00E+03	5.78E-04 AM-243 51.0%	1.53E-04 AM-243 51.0%	5.54E-05 AM-243 51.0%	1.98E-05 AM-243 51.0%	4.96E-06 AM-243 51.0%	2.65E-06 AM-243 51.0%	1.68E-06 AM-243 51.0%	8.77E-07 AM-243 51.0%	5.46E-07 AM-243 51.0%	1.66E-07 AM-243 51.0%
5.00E+03	5.01E-05 AM-243 98.7%	1.32E-05 AM-243 98.7%	4.80E-06 AM-243 98.7%	1.72E-06 AM-243 98.7%	4.29E-07 AM-243 98.7%	2.29E-07 AM-243 98.7%	1.46E-07 AM-243 98.7%	7.59E-08 AM-243 98.7%	4.73E-08 AM-243 98.7%	1.44E-08 AM-243 98.7%
1.00E+04	2.52E-06 AM-243 100.0%	6.65E-07 AM-243 100.0%	2.41E-07 AM-243 100.0%	8.62E-08 AM-243 100.0%	2.16E-08 AM-243 100.0%	1.15E-08 AM-243 100.0%	7.32E-09 AM-243 100.0%	3.81E-09 AM-243 100.0%	2.38E-09 AM-243 100.0%	7.23E-10 AM-243 100.0%

Table 5.37

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
7500 Years After Repository Sealing

Drill Hits Repository Water

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.20E-03 AM-243 80.6%	3.16E-04 AM-243 80.6%	1.15E-04 AM-243 80.6%	4.10E-05 AM-243 80.6%	1.03E-05 AM-243 80.6%	5.48E-06 AM-243 80.6%	3.48E-06 AM-243 80.6%	1.82E-06 AM-243 80.6%	1.13E-06 AM-243 80.6%	3.44E-07 AM-243 80.6%
2.00E+01	1.19E-03 AM-243 80.8%	3.14E-04 AM-243 80.8%	1.14E-04 AM-243 80.8%	4.07E-05 AM-243 80.8%	1.02E-05 AM-243 80.8%	5.43E-06 AM-243 80.8%	3.45E-06 AM-243 80.8%	1.80E-06 AM-243 80.8%	1.12E-06 AM-243 80.8%	3.41E-07 AM-243 80.8%
5.00E+01	1.16E-03 AM-243 81.5%	3.06E-04 AM-243 81.5%	1.11E-04 AM-243 81.5%	3.97E-05 AM-243 81.5%	9.92E-06 AM-243 81.5%	5.29E-06 AM-243 81.5%	3.36E-06 AM-243 81.5%	1.75E-06 AM-243 81.5%	1.09E-06 AM-243 81.5%	3.33E-07 AM-243 81.5%
1.00E+02	1.11E-03 AM-243 82.5%	2.93E-04 AM-243 82.5%	1.06E-04 AM-243 82.5%	3.80E-05 AM-243 82.5%	9.50E-06 AM-243 82.5%	5.07E-06 AM-243 82.5%	3.22E-06 AM-243 82.5%	1.68E-06 AM-243 82.5%	1.05E-06 AM-243 82.5%	3.19E-07 AM-243 82.5%
2.00E+02	1.02E-03 AM-243 84.5%	2.70E-04 AM-243 84.5%	9.77E-05 AM-243 84.5%	3.50E-05 AM-243 84.5%	8.75E-06 AM-243 84.5%	4.67E-06 AM-243 84.5%	2.97E-06 AM-243 84.5%	1.55E-06 AM-243 84.5%	9.64E-07 AM-243 84.5%	2.93E-07 AM-243 84.5%
5.00E+02	8.07E-04 AM-243 89.3%	2.13E-04 AM-243 89.3%	7.73E-05 AM-243 89.3%	2.77E-05 AM-243 89.3%	6.92E-06 AM-243 89.3%	3.69E-06 AM-243 89.3%	2.35E-06 AM-243 89.3%	1.22E-06 AM-243 89.3%	7.62E-07 AM-243 89.3%	2.32E-07 AM-243 89.3%
1.00E+03	5.67E-04 AM-243 94.4%	1.50E-04 AM-243 94.4%	5.43E-05 AM-243 94.4%	1.94E-05 AM-243 94.4%	4.86E-06 AM-243 94.4%	2.59E-06 AM-243 94.4%	1.65E-06 AM-243 94.4%	8.59E-07 AM-243 94.4%	5.35E-07 AM-243 94.4%	1.63E-07 AM-243 94.4%
2.00E+03	2.99E-04 AM-243 98.6%	7.91E-05 AM-243 98.6%	2.87E-05 AM-243 98.6%	1.03E-05 AM-243 98.6%	2.57E-06 AM-243 98.6%	1.37E-06 AM-243 98.6%	8.70E-07 AM-243 98.6%	4.54E-07 AM-243 98.6%	2.83E-07 AM-243 98.6%	8.60E-08 AM-243 98.6%
5.00E+03	4.94E-05 AM-243 100.0%	1.31E-05 AM-243 100.0%	4.73E-06 AM-243 100.0%	1.69E-06 AM-243 100.0%	4.24E-07 AM-243 100.0%	2.26E-07 AM-243 100.0%	1.44E-07 AM-243 100.0%	7.49E-08 AM-243 100.0%	4.67E-08 AM-243 100.0%	1.42E-08 AM-243 100.0%
1.00E+04	2.52E-06 AM-243 100.0%	6.65E-07 AM-243 100.0%	2.41E-07 AM-243 100.0%	8.62E-08 AM-243 100.0%	2.16E-08 AM-243 100.0%	1.15E-08 AM-243 100.0%	7.32E-09 AM-243 100.0%	3.81E-09 AM-243 100.0%	2.38E-09 AM-243 100.0%	7.23E-10 AM-243 100.0%

There is no contaminated area table presented since there were no areas contaminated over 0.5 rem/yr in any case. Americium isotopes are dominant except for some Pu-238 at early times. The low solubility of the plutonium isotopes in the small brine pocket (0.06 m^3) is responsible for their lack of importance at all times. Where Pu-239 and Pu-240 were dominant in the direct hit case, they have been replaced by Am-241 and Am-243 which have much larger solubility limits. The nuclides in a brine pocket are dissolved and, therefore, we use a different set of inhalation DECF's than for the land surface case where they were in an insoluble form.

5.3.3 Granite tank

Tables 5.38 through 5.40 give the annual dose rates resulting from a release of water from a granite repository to the land surface by drilling. The repository's void volume of 2 x 10^6 m^3 has been charged with water from the upper aquifer before canister failure. Then, when the canisters fail, the nuclides from the failed canisters leach or dissolve into the repository water. The inventories of the nuclides in the repository water increase until radioactive decay becomes more important than additional leaching. This overall effort increases the potential dose rates until an event time of 1200 years, when the potential dose rates begin to drop due to decay. For drilling at 1000 years, Am-241 is the dominant nuclide for about 2000 years after the event, but the highest dose rate is only 0.72 rem/yr. After 5000 years, the Am-241 has decayed to lower levels, and Am-243 is the dominant nuclide through 10,000 years. Dose rates are presented for three event times: 1000, 3350, and 7500 years. There is no dose for an event at 200 years because the canisters do not fail until 500 years after sealing.

Here again no contaminated area table is presented since for drilling at 1000 years only a very small area, about 0.2 ha, would be contaminated enough to give a dose rate of more than 0.5 rem/yr. No areas would be contaminated enough to give 0.5 rem/yr or higher from drilling at 3350 or 7500 years.

Table 5.38

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	7.20E-01 AM-241 98.2%	1.90E-01 AM-241 98.2%	6.89E-02 AM-241 98.2%	2.47E-02 AM-241 98.2%	6.17E-03 AM-241 98.2%	3.29E-03 AM-241 98.2%	2.09E-03 AM-241 98.2%	1.09E-03 AM-241 98.2%	6.80E-04 AM-241 98.2%	2.07E-04 AM-241 98.2%
2.00E+01	7.06E-01 AM-241 98.2%	1.87E-01 AM-241 98.2%	6.76E-02 AM-241 98.2%	2.42E-02 AM-241 98.2%	6.05E-03 AM-241 98.2%	3.23E-03 AM-241 96.2%	2.05E-03 AM-241 98.2%	1.07E-03 AM-241 98.2%	6.67E-04 AM-241 98.2%	2.03E-04 AM-241 98.2%
5.00E+01	6.65E-01 AM-241 98.1%	1.76E-01 AM-241 98.1%	6.36E-02 AM-241 98.1%	2.28E-02 AM-241 98.1%	5.70E-03 AM-241 98.1%	3.04E-03 AM-241 98.1%	1.93E-03 AM-241 98.1%	1.01E-03 AM-241 98.1%	6.28E-04 AM-241 98.1%	1.91E-04 AM-241 98.1%
1.00E+02	6.02E-01 AM-241 98.0%	1.59E-01 AM-241 98.0%	5.76E-02 AM-241 98.0%	2.06E-02 AM-241 98.0%	5.16E-03 AM-241 98.0%	2.75E-03 AM-241 98.0%	1.75E-03 AM-241 98.0%	9.12E-04 AM-241 98.0%	5.68E-04 AM-241 98.0%	1.73E-04 AM-241 98.0%
2.00E+02	4.93E-01 AM-241 97.7%	1.30E-01 AM-241 97.7%	4.72E-02 AM-241 97.7%	1.69E-02 AM-241 97.7%	4.23E-03 AM-241 97.7%	2.26E-03 AM-241 97.7%	1.43E-03 AM-241 97.7%	7.47E-04 AM-241 97.7%	4.66E-04 AM-241 97.7%	1.42E-04 AM-241 97.7%
5.00E+02	2.72E-01 AM-241 96.6%	7.20E-02 AM-241 96.6%	2.61E-02 AM-241 96.6%	9.33E-03 AM-241 96.6%	2.33E-03 AM-241 96.6%	1.25E-03 AM-241 96.6%	7.92E-04 AM-241 96.6%	4.13E-04 AM-241 96.6%	2.57E-04 AM-241 96.6%	7.83E-05 AM-241 96.6%
1.00E+03	1.03E-01 AM-241 93.3%	2.72E-02 AM-241 93.3%	9.84E-03 AM-241 93.3%	3.52E-03 AM-241 93.3%	8.81E-04 AM-241 93.3%	4.70E-04 AM-241 93.3%	2.99E-04 AM-241 93.3%	1.56E-04 AM-241 93.3%	9.70E-05 AM-241 93.3%	2.95E-05 AM-241 93.3%
2.00E+03	1.65E-02 AM-241 77.0%	4.37E-03 AM-241 77.0%	1.58E-03 AM-241 77.0%	5.67E-04 AM-241 77.0%	1.42E-04 AM-241 77.0%	7.57E-05 AM-241 77.0%	4.81E-05 AM-241 77.0%	2.51E-05 AM-241 77.0%	1.56E-05 AM-241 77.0%	4.75E-06 AM-241 77.0%
5.00E+03	6.66E-04 AM-243 94.8%	1.76E-04 AM-243 94.8%	6.38E-05 AM-243 94.8%	2.28E-05 AM-243 94.8%	5.71E-06 AM-243 94.8%	3.05E-06 AM-243 94.8%	1.94E-06 AM-243 94.8%	1.01E-06 AM-243 94.8%	6.29E-07 AM-243 94.8%	1.91E-07 AM-243 94.8%
1.00E+04	3.24E-05 AM-243 99.2%	8.56E-06 AM-243 99.2%	3.10E-06 AM-243 99.2%	1.11E-06 AM-243 99.2%	2.78E-07 AM-243 99.2%	1.48E-07 AM-243 99.2%	9.42E-08 AM-243 99.2%	4.91E-08 AM-243 99.2%	3.06E-08 AM-243 99.2%	9.31E-09 AM-243 99.2%

Table 5.39

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
3350 Years After Repository Sealing

Drill Hits Repository Water

TIME (yr)	DISTANCE (meters)									
	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.53E-01 AM-241 66.9%	4.06E-02 AM-241 66.9%	1.47E-02 AM-241 66.9%	5.26E-03 AM-241 66.9%	1.32E-03 AM-241 66.9%	7.02E-04 AM-241 66.9%	4.46E-04 AM-241 66.9%	2.33E-04 AM-241 66.9%	1.45E-04 AM-241 66.9%	4.41E-05 AM-241 66.9%
2.00E+01	1.51E-01 AM-241 66.6%	3.99E-02 AM-241 66.6%	1.45E-02 AM-241 66.6%	5.18E-03 AM-241 66.6%	1.30E-03 AM-241 66.6%	6.91E-04 AM-241 66.6%	4.40E-04 AM-241 66.6%	2.29E-04 AM-241 66.6%	1.43E-04 AM-241 56.6%	4.34E-05 AM-241 66.6%
5.00E+01	1.44E-01 AM-241 65.6%	3.81E-02 AM-241 65.6%	1.38E-02 AM-241 65.6%	4.95E-03 AM-241 65.6%	1.24E-03 AM-241 65.6%	6.60E-04 AM-241 65.6%	4.20E-04 AM-241 65.6%	2.19E-04 AM-241 65.6%	1.36E-04 AM-241 65.6%	4.15E-05 AM-241 65.6%
1.00E+02	1.34E-01 AM-241 64.0%	3.54E-02 AM-241 64.0%	1.28E-02 AM-241 64.0%	4.59E-03 AM-241 64.0%	1.15E-03 AM-241 64.0%	6.12E-04 AM-241 64.0%	3.89E-04 AM-241 64.0%	2.03E-04 AM-241 64.0%	1.26E-04 AM-241 64.0%	3.85E-05 AM-241 64.0%
2.00E+02	1.15E-01 AM-241 60.7%	3.05E-02 AM-241 60.7%	1.10E-02 AM-241 60.7%	3.95E-03 AM-241 60.7%	9.89E-04 AM-241 60.7%	5.28E-04 AM-241 60.7%	3.35E-04 AM-241 60.7%	1.75E-04 AM-241 60.7%	1.09E-04 AM-241 60.7%	3.32E-05 AM-241 60.7%
5.00E+02	7.61E-02 AM-241 50.2%	2.01E-02 AM-241 50.2%	7.29E-03 AM-241 50.2%	2.61E-03 AM-241 50.2%	6.52E-04 AM-241 50.2%	3.48E-04 AM-241 50.2%	2.21E-04 AM-241 50.2%	1.15E-04 AM-241 50.2%	7.19E-05 AM-241 50.2%	2.19E-05 AM-241 50.2%
1.00E+03	4.21E-02 AM-243 66.8%	1.11E-02 AM-243 66.8%	4.03E-03 AM-243 66.8%	1.44E-03 AM-243 66.8%	3.61E-04 AM-243 66.8%	1.92E-04 AM-243 66.8%	1.22E-04 AM-243 66.8%	6.38E-05 AM-243 66.8%	3.97E-05 AM-243 66.8%	1.21E-05 AM-243 66.8%
2.00E+03	1.74E-02 AM-243 89.2%	4.59E-03 AM-243 89.2%	1.66E-03 AM-243 89.2%	5.95E-04 AM-243 89.2%	1.49E-04 AM-243 89.2%	7.94E-05 AM-243 89.2%	5.05E-05 AM-243 89.2%	2.63E-05 AM-243 89.2%	1.64E-05 AM-243 89.2%	4.99E-06 AM-243 89.2%
5.00E+03	2.60E-03 AM-243 99.6%	6.88E-04 AM-243 99.6%	2.49E-04 AM-243 99.6%	8.92E-05 AM-243 99.6%	2.23E-05 AM-243 99.6%	1.19E-05 AM-243 99.6%	7.57E-06 AM-243 99.6%	3.95E-06 AM-243 99.6%	2.46E-06 AM-243 99.6%	7.48E-07 AM-243 99.6%
1.00E+04	1.32E-04 AM-243 99.8%	3.50E-05 AM-243 99.8%	1.27E-05 AM-243 99.8%	4.53E-06 AM-243 99.8%	1.13E-06 AM-243 99.8%	6.05E-07 AM-243 99.8%	3.85E-07 AM-243 99.8%	2.01E-07 AM-243 99.8%	1.25E-07 AM-243 99.8%	3.80E-08 AM-243 99.8%

Table 5.40

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
7500 Years After Repository Sealing

Drill Hits Repository Water

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	7.13E-02 AM-243 99.1%	1.88E-02 AM-243 99.1%	6.82E-03 AM-243 99.1%	2.44E-03 AM-243 99.1%	6.11E-04 AM-243 99.1%	3.26E-04 AM-243 99.1%	2.07E-04 AM-243 99.1%	1.08E-04 AM-243 99.1%	6.73E-05 AM-243 99.1%	2.05E-05 AM-243 99.1%
2.00E+01	7.08E-02 AM-243 99.1%	1.87E-02 AM-243 99.1%	6.78E-03 AM-243 99.1%	2.43E-03 AM-243 99.1%	6.07E-04 AM-243 99.1%	3.24E-04 AM-243 99.1%	2.06E-04 AM-243 99.1%	1.07E-04 AM-243 99.1%	6.69E-05 AM-243 99.1%	2.04E-05 AM-243 99.1%
5.00E+01	6.95E-02 AM-243 99.2%	1.84E-02 AM-243 99.2%	6.66E-03 AM-243 99.2%	2.38E-03 AM-243 99.2%	5.96E-04 AM-243 99.2%	3.18E-04 AM-243 99.2%	2.02E-04 AM-243 99.2%	1.05E-04 AM-243 99.2%	6.57E-05 AM-243 99.2%	2.00E-05 AM-243 99.2%
1.00E+02	6.74E-02 AM-243 99.2%	1.78E-02 AM-243 99.2%	6.46E-03 AM-243 99.2%	2.31E-03 AM-243 99.2%	5.78E-04 AM-243 99.2%	3.09E-04 AM-243 99.2%	1.96E-04 AM-243 99.2%	1.02E-04 AM-243 99.2%	6.37E-05 AM-243 99.2%	1.94E-05 AM-243 99.2%
2.00E+02	6.35E-02 AM-243 99.3%	1.68E-02 AM-243 99.3%	6.08E-03 AM-243 99.3%	2.18E-03 AM-243 99.3%	5.44E-04 AM-243 99.3%	2.90E-04 AM-243 99.3%	1.85E-04 AM-243 99.3%	9.62E-05 AM-243 99.3%	5.99E-05 AM-243 99.3%	1.82E-05 AM-243 99.3%
5.00E+02	5.30E-02 AM-243 99.6%	1.40E-02 AM-243 99.6%	5.07E-03 AM-243 99.6%	1.82E-03 AM-243 99.6%	4.54E-04 AM-243 99.6%	2.42E-04 AM-243 99.6%	1.54E-04 AM-243 99.6%	8.03E-05 AM-243 99.6%	5.00E-05 AM-243 99.6%	1.52E-05 AM-243 99.6%
1.00E+03	3.93E-02 AM-243 99.7%	1.04E-02 AM-243 99.7%	3.76E-03 AM-243 99.7%	1.35E-03 AM-243 99.7%	3.37E-04 AM-243 99.7%	1.80E-04 AM-243 99.7%	1.14E-04 AM-243 99.7%	5.95E-05 AM-243 99.7%	3.71E-05 AM-243 99.7%	1.13E-05 AM-243 99.7%
2.00E+03	2.16E-02 AM-243 99.8%	5.71E-03 AM-243 99.8%	2.07E-03 AM-243 99.8%	7.41E-04 AM-243 99.8%	1.85E-04 AM-243 99.8%	9.89E-05 AM-243 99.8%	6.29E-05 AM-243 99.8%	3.28E-05 AM-243 99.8%	2.04E-05 AM-243 99.8%	6.22E-06 AM-243 99.8%
5.00E+03	3.62E-03 AM-243 99.9%	9.57E-04 AM-243 99.9%	3.47E-04 AM-243 99.9%	1.24E-04 AM-243 99.9%	3.10E-05 AM-243 99.9%	1.66E-05 AM-243 99.9%	1.05E-05 AM-243 99.9%	5.49E-06 AM-243 99.9%	3.42E-06 AM-243 99.9%	1.04E-06 AM-243 99.9%
1.00E+04	1.84E-04 AM-243 99.9%	4.87E-05 AM-243 99.9%	1.76E-05 AM-243 99.9%	6.32E-06 AM-243 99.9%	1.58E-06 AM-243 99.9%	8.43E-07 AM-243 99.9%	5.36E-07 AM-243 99.9%	2.79E-07 AM-243 99.9%	1.74E-07 AM-243 99.9%	5.30E-08 AM-243 99.9%

5.4. Release to the Aquifer due to Shaft Seal Leakage

There are four main shafts in the model repository, each with a cross-sectional area of 25 m^2. The shafts are sealed initially to a permeability of 3.15 x 10^{-3} m/yr but degrade over 10,000 years to 31.5 m/yr. We modeled releases through one shaft from a granite repository; the smaller amount of water in a bedded salt repository and the tendency of the salt to seal itself make this kind of release much less important in salt. There is no release from a granite repository until 500 years, when the canisters fail. This model differs from the drilling event by the greater cross-sectional area of the shaft as compared with the borehole and the lower initial permeability. The lower permeability counteracts, to some degree, the increased flow area. Table 5.41 gives the annual dose rates resulting from this type of release. The early annual dose rates, for the first 100 years, are mainly from Sr-90. Sn-126 dominates after 100 years until some time between 500 and 1000 years. All dose rates are small until Am-241 appears at 1000 years and gradually increase to the maximum dose rate of 16,000 rem/yr at 10,000 years, comparable to the dose rate from borehole drilling into a brine pocket or granite tank 1000 years after sealing (Sections 5.1.2 and 5.1.3). Sn-126 and Tc-99 have moved farther downstream. Am-241 dominates the dose rate to about 5000 years, when Am-243 becomes dominant. Table 5.42 gives the extent of the contaminated areas which again are roughly comparable to those from drilling into a brine pocket or granite tank.

Table 5.41

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released from the GRANITE Repository

Shaft Seal Leakage

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.41E-05 SR -90 68.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	4.72E-04 SR -90 68.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	2.24E-03 SR -90 66.0%	6.62E-04 SR -90 66.0%	1.48E-05 SR -90 65.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	3.42E-03 SR -90 56.2%	1.55E-03 SR -90 57.1%	5.52E-04 SR -90 57.1%	8.70E-06 SR -90 56.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.21E-02 SN-126 72.0%	1.86E-03 CS-135 40.2%	1.00E-03 CS-135 40.2%	3.52E-04 CS-135 40.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.19E-01 SN-126 39.0%	3.81E-02 SN-126 79.3%	5.36E-03 CS-135 55.6%	2.94E-03 CS-135 58.6%	8.39E-04 CS-135 58.6%	2.22E-04 CS-135 58.5%	7.63E-06 CS-135 57.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.19E+02 AM-241 96.1%	2.33E-01 SN-126 88.3%	9.36E-02 SN-126 80.3%	1.26E-02 CS-135 57.0%	5.60E-03 CS-135 60.1%	3.39E-03 CS-135 60.1%	2.04E-03 CS-135 60.0%	5.55E-04 CS-135 60.0%	1.76E-05 CS-135 59.7%	0.0 NONE 0.0%
2.00E+03	8.02E+03 AM-241 86.9%	9.40E-01 SN-126 90.9%	5.33E-01 SN-126 88.9%	2.18E-01 SN-126 81.5%	2.23E-02 CS-135 62.9%	1.62E-02 CS-135 62.9%	1.24E-02 CS-135 62.9%	7.60E-03 CS-135 62.9%	4.64E-03 CS-135 62.9%	4.23E-05 CS-135 62.7%
5.00E+03	8.01E+03 AM-243 91.4%	2.54E+03 AM-243 91.3%	2.82E+01 AM-243 89.0%	1.76E+00 SN-126 90.8%	6.05E-01 SN-126 83.9%	2.29E-01 SN-126 66.5%	6.92E-02 CS-135 65.0%	4.79E-02 CS-135 70.6%	3.80E-02 CS-135 70.6%	1.76E-02 CS-135 70.6%
1.00E+04	1.57E+04 AM-243 99.9%	7.68E+03 AM-243 99.8%	3.10E+03 AM-243 99.7%	4.57E+01 AM-243 87.8%	2.79E+00 SN-126 91.1%	1.81E+00 SN-126 89.0%	1.20E+00 SN-126 85.8%	4.59E-01 SN-126 71.0%	1.24E-01 CS-135 72.4%	6.66E-02 CS-135 81.0%

Table 5.42

Area (ha*) of the Aquifer Contaminated
Above the Specified Dose Rate Levels
Due to Shaft Seal Leakage

Time After Drilling (yr)	Dose Levels (rem/yr)			
	0.5	5	50	500
0-500	0	0	0	0
1,000	0.35	0.29	0.22	0.12
2,000	0.31	0.25	0.17	0
5,000	2.2	1.4	0	0
10,000	6.6	2.9	0	0

*1 ha = 10^4 square meters

Table 5.43

Summary of Maximum Individual Annual Dose Rates

Event Type/ Pathway and, Event time (yr)	Maximum Dose (rem/yr)	Nuclide Donating Majority of Dose And its Percentage		Location and Time of Maximum
Drilling Hit on Waste/Aquifer				
200	2000	Am-241	97.7	1000 years, 20 meters
1,000	625	Am-241	93.1	1000 years, 20 meters
3,350	51.3	Am-243	67.5	1000 years, 20 meters
7,500	23.8	Am-243	99.7	1000 years, 20 meters
Drilling into a Brine Pocket/Aquifer				
200	3970	Am-241	97.7	1000 years, 20 meters
1,000	1150	Am-241	93.1	1000 years, 20 meters
3,350	74.3	Am-243	67.5	1000 years, 20 meters
7,500	22.8	Am-243	99.6	1000 years, 20 meters
Drilling into the Granite Tank/Aquifer				
500	1300	Am-241	87.0	2000 years, 20 meters
1,000	1830	Am-241	93.1	1000 years, 20 meters
3,350	261	Am-243	67.5	1000 years, 20 meters
7,500	66.4	Am-243	99.8	1000 years, 20 meters
Faulting Hit on Waste/Aquifer				
200	1970	Am-241	98.8	500 years, 4000 meters
1,000	601	Am-241	96.5	500 years, 4000 meters
3,350	36.3	Am-243	66.6	1000 years, 4000 meters
7,500	21.1	Am-243	96.2	2000 years, 4000 meters
Faulting Hit on the Granite Tank/Aquifer				
200	563,000	Am-241	99.1	500 years, 4000 meters
1,000	640,000	Am-241	98.2	100 years, 4000 meters
3,350	83,800	Am-241	66.3	100 years, 4000 meters
7,500	36,400	Am-243	99.4	100 years, 4000 meters
Direct Drilling Hit on Waste/Land Surface				
200	28.8	Am-241	70.7	10 years, 20 meters
1,000	11.2	Am-241	54.2	10 years, 20 meters
3,350	4.52	Pu-240	50.4	10 years, 20 meters
7,500	3.31	Pu-239	52.7	10 years, 20 meters
Drilling into a Brine Pocket/Land Surface				
200	0.07	Pu-238	55.0	10 years, 20 meters
1,000	0.03	Am-241	92.3	10 years, 20 meters
3,350	0.03	Am-241	94.2	10 years, 20 meters
7,500	0.02	Am-243	89.3	10 years, 20 meters

Table 5.43 (continued)

Drilling into the Granite Tank/Land Surface				
1000	0.72	Am-241	98.2	10 years, 20 meters
3350	0.15	Am-241	66.9	10 years, 20 meters
7500	0.07	Am-243	99.1	10 years, 20 meters
Shaft Seal Leakage/Aquifer				
500	1300	Am-241	95.3	1000 years, 20 meters

Chapter 6

Results of the Sensitivity Analysis

In this chapter we examine the effect on annual dose rates when we assign different values to the repository system characteristics. We varied six parameters to study their impact on dose rates:

1. Canister Life
2. Removal of solubility limits
3. Leach rates from the canisters
4. Retardation factors in the aquifer
5. Degrading permeability of the borehole
6. Groundwater velocity

All results in this chapter are from an event occurring 1000 years after the repository was sealed. Each event is considered in a separate section of Chapter 6. All results are summarized in Section 6.7. The source term and transport equations in Chapter 4 are used in these analyses.

6.1 Effect of Varying Canister Life

In the reference case we used canister lives of 100 years for salt and 500 years for granite. In this section we look at the effect of changing the canister lives to 0 years (they fail immediately) and 1000 years. Changing the canister life has no effect on cases in which canisters are destroyed either by faulting or by drilling. In cases where the event releases repository water to the environment the concentration of leach-limited nuclides in that water depends on the length of time the waste has been in contact with water, and therefore the canister life does affect these releases. Solubility-limited nuclides are affected by canister life only when the canister remains intact until the event, since the model considers that they reach their solubility limits quickly.

6.1.1 Release to the aquifer due to drilling

Granite tank

Tables 6.1 and 6.7 give the annual dose rates and the contaminated areas, respectively, from drinking water after a drilling release to the aquifer from repository water in granite, when canister life is zero and the event occurs 1000 years after repository sealing. Tables 6.2 and 6.7 present the same data for a 1000-year canister life. The largest dose rates are 6800 rem/yr for zero canister life and 1500 rem/yr for 1000-year life. These values may be compared with 1800 rem/yr for the 500-year canister life in Table 5.17. The peak dose rate for the longest canister life is reached 2000 years after drilling instead of 1000 years for the zero and 500-year canisters. This is because the nuclides do not have as much time to leach into the tank as they do when the canisters fail immediately. In Table 6.2 at 2000 years after drilling (3000 years since sealing) and 20 meters, the Am-241 has been leaching for 2000 years, while in Table 6.1 the Am-241 at 1000 years after drilling (2000 years since sealing) and 20 meters has been leaching for 2000 years also. The lower annual dose rate in Table 6.2 is due mostly to the extra 1000 years of decay.

When we compare these doses with those from the same event with a 500-year canister life, we see that the differences are small. This is perhaps best shown in the contaminated area results in Table 6.7. The contaminated areas when canister life is zero are only slightly larger than those when canister life is 500 years (Table 5.21). Increasing canister life to 1000 years results in contaminated areas somewhat smaller than those when canister life is 500 years. When canisters last 1000 years, areas contaminated to a level of 0.5 rem/yr are generally from 80 to 100% as large as the areas contaminated to this level when canisters fail immediately. In contrast, areas contaminated to a level of 50 rem/yr, when canisters last 1000 years, average only 60% as large as those contaminated to this level when the canisters fail immediately.

Brine pocket

Tables 6.3 and 6.4 show the effect of a varying canister life on releases to the aquifer from drilling into a salt repository. The annual dose rates throughout the tables are practically the same as those resulting from the same event with a 100-year canister life (Table 5.12). The americium isotopes, which dominate this release, reach their solubility limit in the brine pocket very quickly. The longer canister life yields slightly larger annual dose rates. This is due to the term "$\exp[-L(t-t_c)]$" which can be rearranged to give "$\exp(-Lt)\exp(+Lt_c)$". The second factor increases as the canister life, t_c, increases. Dose rates are below one rem/yr until Am-241 appears at a dose time of 1000 years. As the Am-241 decays, Am-243 predominates, and Sn-126 is dominant at larger distances. The contaminated areas (Table 6.7) differ by only a few hundred square meters; in effect they are the same. For this event, the canister life (over the range of 0 to 1000 years) has no impact on annual dose rates or on the extent of contamination because the americium isotopes which are responsible for over 90% of the total dose, reach their solubility limits quickly.

6.1.2 Release to the aquifer due to faulting

Tables 6.5 and 6.6 show annual dose rates resulting from a fault. Table 6.5 is for a zero canister life and Table 6.6 is for a 1000-year canister life. For a zero canister life the highest annual dose rate occurs 100 years after the event. The value is about 630,000 rem/yr, compared to a value of about 340,000 rem/yr for the 500-year canister life case (Table 5.26). The longer canister life produces a considerably smaller maximum dose, about 100,000 rem/yr, at a later peak dose time, 500 years. In both cases Am-241 is the most prominent nuclide before 5000 years while Am-243 is after 5000 years.

6.1.3 Release to the land surface

Table 6.8 gives the annual inhalation dose rates from a brine pocket release to the land surface when the canisters fail immediately

Table 6.1

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
Canister Life = Zero

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
	2.08E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.00E+01	CS-135	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE
	58.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	2.10E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.00E+01	CS-135	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE
	58.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	2.13E-02	1.34E-02	9.31E-03	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.00E+01	CS-135	CS-135	CS-135	NONE	NONE	NONE	NONE	NONE	NONE	NONE
	58.8%	58.8%	58.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	2.60E-01	1.37E-02	9.57E-03	6.58E-03	0.0	0.0	0.0	0.0	0.0	0.0
1.00E+02	SN-126	CS-135	CS-135	CS-135	NONE	NONE	NONE	NONE	NONE	NONE
	91.6%	58.9%	58.9%	58.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	2.75E-01	1.44E-02	1.01E-02	6.94E-03	0.0	0.0	0.0	0.0	0.0	0.0
2.00E+02	SN-126	CS-135	CS-135	CS-135	NONE	NONE	NONE	NONE	NONE	NONE
	91.7%	59.2%	59.2%	59.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	3.17E-01	1.89E-01	1.19E-01	7.91E-03	4.69E-03	3.61E-03	2.92E-03	0.0	0.0	0.0
5.00E+02	SN-126	SN-126	SN-126	CS-135	CS-135	CS-135	CS-135	NONE	NONE	NONE
	91.8%	91.4%	90.4%	60.1%	60.1%	60.1%	60.1%	0.0%	0.0%	0.0%
	6.87E+03	2.29E-01	1.49E-01	8.60E-02	5.59E-03	4.38E-03	3.63E-03	2.68E-03	2.05E-03	0.0
1.00E+03	AM-241	SN-126	SN-126	SN-126	CS-135	CS-135	CS-135	CS-135	CS-135	NONE
	93.1%	91.7%	91.1%	89.2%	61.5%	61.5%	61.5%	61.5%	61.5%	0.0%
	2.74E+03	2.93E-01	1.97E-01	1.25E-01	6.93E-03	5.52E-03	4.66E-03	3.59E-03	2.92E-03	1.42E-03
2.00E+03	AM-241	SN-126	SN-126	SN-126	CS-135	CS-135	CS-135	CS-135	CS-135	CS-135
	76.6%	92.2%	91.9%	91.0%	64.2%	64.2%	64.2%	64.2%	64.2%	64.2%
	8.35E+02	4.46E+02	1.63E+02	1.96E-01	1.06E-01	7.08E-02	4.33E-02	5.02E-03	4.25E-03	2.71E-03
5.00E+03	AM-243	AM-243	AM-243	SN-126	SN-126	SN-126	SN-126	CS-135	CS-135	CS-135
	95.5%	95.5%	99.7%	92.6%	91.4%	89.6%	85.5%	71.8%	71.8%	71.8%
	6.98E+02	4.12E+02	2.51E+02	8.14E+01	1.53E-01	1.17E-01	9.42E-02	6.19E-02	3.32E-02	3.47E-03
1.00E+04	AM-243	AM-243	AM-243	AM-243	SN-126	SN-126	SN-126	SN-126	SN-126	CS-135
	99.9%	99.9%	99.8%	99.7%	93.1%	92.7%	92.1%	90.3%	84.6%	81.9%

Table 6.2

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
Canister Life = 1000 years

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.71E-05 TC -99 39.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	2.35E-04 CS-135 57.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	8.77E-04 CS-135 58.4%	3.62E-04 CS-135 58.1%	2.62E-05 CS-135 52.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	3.10E-03 SN-126 38.3%	1.02E-03 CS-135 58.7%	5.03E-04 CS-135 58.6%	3.48E-05 CS-135 55.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.90E-02 SN-126 86.7%	2.27E-03 CS-135 59.1%	1.40E-03 CS-135 59.1%	6.93E-04 CS-135 59.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	9.70E-02 SN-126 90.8%	4.31E-02 SN-126 87.2%	6.36E-03 SN-126 41.3%	2.40E-03 CS-135 60.0%	1.02E-03 CS-135 60.0%	4.75E-04 CS-135 59.9%	7.22E-05 CS-135 59.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	3.28E+02 AM-241 93.1%	1.05E-01 SN-126 90.7%	5.59E-02 SN-126 87.8%	8.28E-03 SN-126 44.3%	2.54E-03 CS-135 61.5%	1.80E-03 CS-135 61.5%	1.31E-03 CS-135 61.4%	6.25E-04 CS-135 61.4%	9.83E-05 CS-135 61.1%	0.0 NONE 0.0%
2.00E+03	1.47E+03 AM-241 76.6%	1.97E-01 SN-126 91.9%	1.26E-01 SN-126 91.1%	6.88E-02 SN-126 88.7%	4.64E-03 CS-135 64.2%	3.60E-03 CS-135 64.2%	2.95E-03 CS-135 64.2%	2.12E-03 CS-135 64.2%	1.57E-03 CS-135 64.2%	1.30E-04 CS-135 64.0%
5.00E+03	7.01E+02 AM-243 95.5%	3.38E+02 AM-243 95.5%	3.33E+01 AM-243 98.5%	1.65E-01 SN-126 92.4%	8.14E-02 SN-126 90.4%	4.55E-02 SN-126 86.1%	1.29E-02 SN-126 58.1%	4.27E-03 CS-135 71.8%	3.57E-03 CS-135 71.8%	2.15E-03 CS-135 71.8%
1.00E+04	6.56E+02 AM-243 99.9%	3.81E+02 AM-243 99.9%	2.21E+02 AM-243 99.8%	2.77E+01 AM-243 99.1%	1.42E-01 SN-126 92.9%	1.06E-01 SN-126 92.4%	8.33E-02 SN-126 91.6%	4.91E-02 SN-126 88.5%	1.43E-02 SN-126 66.4%	3.22E-03 CS-135 81.9%

Table 6.3

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
Canister Life = Zero

TIME (yr)	DISTANCE (meters)									
	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.53E-03 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	3.55E-03 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	3.54E-03 CS-135 58.7%	2.24E-03 CS-135 58.7%	1.59E-03 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	4.40E-02 SN-126 92.0%	2.22E-03 CS-135 58.8%	1.58E-03 CS-135 58.8%	1.12E-03 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	4.35E-02 SN-126 92.0%	2.19E-03 CS-135 59.1%	1.55E-03 CS-135 59.1%	1.10E-03 CS-135 59.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	4.21E-02 SN-126 92.1%	2.70E-02 SN-126 92.2%	1.95E-02 SN-126 92.4%	1.06E-03 CS-135 60.0%	6.78E-04 CS-135 60.0%	5.60E-04 CS-135 60.0%	4.90E-04 CS-135 60.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.13E+03 AM-241 93.1%	2.55E-02 SN-126 92.4%	1.85E-02 SN-126 92.5%	1.36E-02 SN-126 92.8%	6.29E-04 CS-135 61.4%	5.20E-04 CS-135 61.4%	4.56E-04 CS-135 61.4%	3.81E-04 CS-135 61.4%	3.38E-04 CS-135 61.4%	0.0 NONE 0.0%
2.00E+03	2.75E+02 AM-241 76.6%	2.28E-02 SN-126 92.6%	1.65E-02 SN-126 92.7%	1.22E-02 SN-126 93.0%	5.43E-04 CS-135 64.1%	4.49E-04 CS-135 64.1%	3.94E-04 CS-135 64.1%	3.30E-04 CS-135 64.1%	2.93E-04 CS-135 64.1%	2.28E-04 CS-135 64.1%
5.00E+03	3.76E+01 AM-243 95.5%	2.76E+01 AM-243 95.5%	2.48E+01 AM-243 95.5%	8.73E-03 SN-126 93.6%	6.37E-03 SN-126 94.4%	5.84E-03 SN-126 95.0%	5.66E-03 SN-126 95.4%	2.17E-04 CS-135 71.7%	1.92E-04 CS-135 71.7%	1.51E-04 CS-135 71.7%
1.00E+04	1.39E+01 AM-243 99.7%	1.03E+01 AM-243 99.7%	9.05E+00 AM-243 99.8%	1.04E+01 AM-243 99.9%	3.73E-03 SN-126 94.9%	3.37E-03 SN-126 95.3%	3.27E-03 SN-126 95.8%	3.41E-03 SN-126 96.6%	3.70E-03 SN-126 97.2%	7.98E-05 CS-135 81.7%

Table 6.4

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
Canister Life = 1000 years

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.91E-03 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	3.93E-03 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	3.91E-03 CS-135 58.7%	2.48E-03 CS-135 58.7%	1.75E-03 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	4.86E-02 SN-126 92.0%	2.46E-03 CS-135 58.8%	1.74E-03 CS-135 58.8%	1.24E-03 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	4.81E-02 SN-126 92.0%	2.42E-03 CS-135 59.1%	1.72E-03 CS-135 59.1%	1.22E-03 CS-135 59.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	4.65E-02 SN-126 92.1%	2.98E-02 SN-126 92.2%	2.15E-02 SN-126 92.4%	1.17E-03 CS-135 60.0%	7.49E-04 CS-135 60.0%	6.19E-04 CS-135 60.0%	5.42E-04 CS-135 60.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.25E+03 AM-241 93.1%	2.82E-02 SN-126 92.4%	2.04E-02 SN-126 92.5%	1.51E-02 SN-126 92.8%	6.95E-04 CS-135 61.4%	5.75E-04 CS-135 61.4%	5.04E-04 CS-135 61.4%	4.21E-04 CS-135 61.4%	3.74E-04 CS-135 61.4%	0.0 NONE 0.0%
2.00E+03	3.04E+02 AM-241 76.6%	2.52E-02 SN-126 92.6%	1.82E-02 SN-126 92.7%	1.35E-02 SN-126 93.0%	6.00E-04 CS-135 64.1%	4.96E-04 CS-135 64.1%	4.35E-04 CS-135 64.1%	3.64E-04 CS-135 64.1%	3.24E-04 CS-135 64.1%	2.51E-04 CS-135 64.1%
5.00E+03	4.15E+01 AM-243 95.5%	3.06E+01 AM-243 95.5%	2.74E+01 AM-243 95.5%	9.65E-03 SN-126 93.6%	7.04E-03 SN-126 94.4%	6.46E-03 SN-126 95.0%	6.26E-03 SN-126 95.4%	2.39E-04 CS-135 71.7%	2.12E-04 CS-135 71.7%	1.66E-04 CS-135 71.7%
1.00E+04	1.53E+01 AM-243 99.7%	1.13E+01 AM-243 99.8%	1.00E+01 AM-243 99.8%	1.15E+01 AM-243 99.9%	4.12E-03 SN-126 94.9%	3.73E-03 SN-126 95.3%	3.61E-03 SN-126 95.8%	3.77E-03 SN-126 96.6%	4.09E-03 SN-126 97.2%	8.82E-05 CS-135 81.7%

Table 6.5

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Repository Water Affected
Canister Life = Zero

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	7.30E+01 SN-126 53.9%	7.58E+01 SN-126 51.9%	7.58E+01 SN-126 51.9%	7.58E+01 SN-126 51.9%	7.58E+01 SN-126 51.9%	7.58E+01 SN-126 51.9%	7.58E+01 SN-126 51.9%	7.58E+01 SN-126 51.9%	7.58E+01 SN-126 51.9%	7.58E+01 SN-126 51.9%
2.00E+01	4.83E+01 SN-126 88.7%	7.00E+01 SN-126 61.1%	7.00E+01 SN-126 61.1%	7.00E+01 SN-126 61.1%	7.00E+01 SN-126 61.1%	7.00E+01 SN-126 61.1%	7.00E+01 SN-126 61.1%	7.00E+01 SN-126 61.1%	7.00E+01 SN-126 61.1%	7.00E+01 SN-126 61.1%
5.00E+01	3.26E+05 AM-241 95.4%	3.26E+05 AM-241 95.4%	3.26E+05 AM-241 95.4%	3.26E+05 AM-241 95.4%	3.26E+05 AM-241 95.4%	3.26E+05 AM-241 95.4%	3.26E+05 AM-241 95.4%	3.26E+05 AM-241 95.4%	3.26E+05 AM-241 95.4%	3.26E+05 AM-241 95.4%
1.00E+02	6.32E+05 AM-241 95.1%	6.32E+05 AM-241 95.1%	6.32E+05 AM-241 95.1%	6.32E+05 AM-241 95.1%	6.32E+05 AM-241 95.1%	6.32E+05 AM-241 95.1%	6.32E+05 AM-241 95.1%	6.32E+05 AM-241 95.1%	6.32E+05 AM-241 95.1%	6.32E+05 AM-241 95.1%
2.00E+02	4.30E+05 AM-241 94.4%	4.30E+05 AM-241 94.4%	4.30E+05 AM-241 94.4%	4.30E+05 AM-241 94.4%	4.30E+05 AM-241 94.4%	4.30E+05 AM-241 94.4%	4.30E+05 AM-241 94.4%	4.30E+05 AM-241 94.4%	4.30E+05 AM-241 94.4%	4.30E+05 AM-241 94.4%
5.00E+02	2.43E+05 AM-241 91.6%	2.43E+05 AM-241 91.6%	2.43E+05 AM-241 91.6%	2.43E+05 AM-241 91.6%	2.43E+05 AM-241 91.6%	2.43E+05 AM-241 91.6%	2.43E+05 AM-241 91.6%	2.43E+05 AM-241 91.6%	2.43E+05 AM-241 91.6%	2.43E+05 AM-241 91.6%
1.00E+03	7.27E+04 AM-241 84.2%	1.29E+05 AM-241 84.2%	1.29E+05 AM-241 84.2%	1.29E+05 AM-241 84.2%	1.29E+05 AM-241 84.2%	1.29E+05 AM-241 84.2%	1.29E+05 AM-241 84.2%	1.29E+05 AM-241 84.2%	1.29E+05 AM-241 84.2%	1.29E+05 AM-241 84.2%
2.00E+03	2.18E+04 AM-241 55.8%	4.84E+04 AM-241 55.8%	4.84E+04 AM-241 55.8%	4.84E+04 AM-241 55.8%	4.84E+04 AM-241 55.8%	4.84E+04 AM-241 55.8%	4.84E+04 AM-241 55.8%	4.84E+04 AM-241 55.8%	4.84E+04 AM-241 55.8%	4.84E+04 AM-241 55.8%
5.00E+03	5.84E+03 AM-243 36.0%	1.08E+04 AM-243 36.0%	1.75E+04 AM-243 36.0%	2.09E+04 AM-243 36.0%	2.09E+04 AM-243 35.9%	2.09E+04 AM-243 35.9%	2.09E+04 AM-243 35.9%	2.09E+04 AM-243 35.9%	2.09E+04 AM-243 35.9%	2.09E+04 AM-243 35.9%
1.00E+04	2.48E+03 PU-239 36.8%	4.57E+03 PU-239 36.8%	7.40E+03 PU-239 36.8%	1.32E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%

Table 6.6

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Repository Water Affected
Canister Life = 1000 years

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	4.52E-01 TC -99 36.5%	4.52E-01 TC -99 36.5%	4.52E-01 TC -99 36.5%	4.52E-01 TC -99 36.5%	4.52E-01 TC -99 36.5%	4.52E-01 TC -99 36.5%	4.52E-01 TC -99 36.5%	4.52E-01 TC -99 36.5%	4.52E-01 TC -99 36.5%	4.52E-01 TC -99 36.5%
2.00E+01	1.06E+00 SN-126 55.6%	1.24E+00 SN-126 47.9%	1.24E+00 SN-126 47.9%	1.24E+00 SN-126 47.9%	1.24E+00 SN-126 47.9%	1.24E+00 SN-126 47.9%	1.24E+00 SN-126 47.9%	1.24E+00 SN-126 47.9%	1.24E+00 SN-126 47.9%	1.24E+00 SN-126 47.9%
5.00E+01	4.41E+02 AM-241 95.0%	4.41E+02 AM-241 94.9%	4.41E+02 AM-241 94.8%	4.41E+02 AM-241 94.8%	4.41E+02 AM-241 94.8%	4.41E+02 AM-241 94.8%	4.41E+02 AM-241 94.8%	4.41E+02 AM-241 94.8%	4.41E+02 AM-241 94.8%	4.41E+02 AM-241 94.8%
1.00E+02	3.46E+04 AM-241 95.1%	3.46E+04 AM-241 95.1%	3.46E+04 AM-241 95.1%	3.46E+04 AM-241 95.1%	3.46E+04 AM-241 95.1%	3.46E+04 AM-241 95.1%	3.46E+04 AM-241 95.1%	3.46E+04 AM-241 95.1%	3.46E+04 AM-241 95.1%	3.46E+04 AM-241 95.1%
2.00E+02	7.44E+04 AM-241 94.4%	7.44E+04 AM-241 94.4%	7.44E+04 AM-241 94.4%	7.44E+04 AM-241 94.4%	7.44E+04 AM-241 94.4%	7.44E+04 AM-241 94.4%	7.44E+04 AM-241 94.4%	7.44E+04 AM-241 94.4%	7.44E+04 AM-241 94.4%	7.44E+04 AM-241 94.4%
5.00E+02	1.04E+05 AM-241 91.6%	1.04E+05 AM-241 91.6%	1.04E+05 AM-241 91.6%	1.04E+05 AM-241 91.6%	1.04E+05 AM-241 91.6%	1.04E+05 AM-241 91.6%	1.04E+05 AM-241 91.6%	1.04E+05 AM-241 91.6%	1.04E+05 AM-241 91.6%	1.04E+05 AM-241 91.6%
1.00E+03	8.03E+04 AM-241 84.2%	8.14E+04 AM-241 84.2%	8.14E+04 AM-241 84.2%	8.14E+04 AM-241 84.2%	8.14E+04 AM-241 84.2%	8.14E+04 AM-241 84.2%	8.14E+04 AM-241 84.2%	8.14E+04 AM-241 84.2%	8.14E+04 AM-241 84.2%	8.14E+04 AM-241 84.2%
2.00E+03	2.41E+04 AM-241 55.6%	3.96E+04 AM-241 55.8%	3.96E+04 AM-241 55.8%	3.96E+04 AM-241 55.8%	3.96E+04 AM-241 55.8%	3.96E+04 AM-241 55.8%	3.96E+04 AM-241 55.8%	3.96E+04 AM-241 55.8%	3.96E+04 AM-241 55.8%	3.96E+04 AM-241 55.8%
5.00E+03	6.45E+03 AM-243 36.0%	1.19E+04 AM-243 36.0%	1.93E+04 AM-243 36.0%	2.00E+04 AM-243 36.0%	2.00E+04 AM-243 35.9%	2.00E+04 AM-243 35.9%	2.00E+04 AM-243 35.9%	2.00E+04 AM-243 35.9%	2.00E+04 AM-243 35.9%	2.00E+04 AM-243 35.9%
1.00E+04	2.74E+03 PU-239 36.8%	5.05E+03 PU-239 36.8%	8.18E+03 PU-239 36.8%	1.46E+04 PU-239 36.8%	1.52E+04 PU-239 36.8%	1.52E+04 PU-239 36.8%	1.52E+04 PU-239 36.8%	1.52E+04 PU-239 36.8%	1.52E+04 PU-239 36.8%	1.52E+04 PU-239 36.8%

Table 6.7

Area (ha*) of the Aquifer Contaminated
Above the Specified Dose Rate Levels
Because of Drilling 1000 Years after Sealing

Varying canister life

Repository type/ Canister Life (yr)	Length of time after drilling (yr)	Dose Rate Levels (rem/yr) 0.5	5	50	500
Granite/1000	0-500	0	0	0	0
	1000	0.30	0.23	0.14	0
	2000	0.33	0.27	0.19	0.04
	5000	2.28	1.47	0.32	0
	10000	7.22	4.08	0	0
Granite/0	0-500	0	0	0	0
	1000	0.37	0.32	0.26	0.17
	2000	0.34	0.29	0.22	0.11
	5000	2.59	1.93	0.86	0
	10000	8.03	5.41	0	0
Salt/1000	0-500	0	0	0	0
	1000	0.35	0.29	0.22	0.12
	2000	0.31	0.25	0.17	0
	5000	2.29	1.51	0	0
	10000	6.90	3.53	0	0
Salt/0	0-500	0	0	0	0
	1000	0.35	0.29	0.22	0.11
	2000	0.31	0.25	0.16	0
	5000	2.27	1.47	0	0
	10000	6.79	3.31	0	0

*1 hectare (ha) = 10^4 square meters

Table 6.8

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
Canister Life = Zero

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.91E-01 AM-241 90.1%	7.68E-02 AM-241 90.1%	2.78E-02 AM-241 90.1%	9.97E-03 AM-241 90.1%	2.49E-03 AM-241 90.1%	1.33E-03 AM-241 90.1%	8.46E-04 AM-241 90.1%	4.41E-04 AM-241 90.1%	2.75E-04 AM-241 90.[illegible]	8.36E-05 AM-241 90.1%
2.00E+01	2.84E-01 AM-241 90.3%	7.52E-02 AM-241 90.3%	2.72E-02 AM-241 90.3%	9.75E-03 AM-241 90.3%	2.44E-03 AM-241 90.3%	1.30E-03 AM-241 90.3%	8.27E-04 AM-241 90.3%	4.31E-04 AM-241 90.3%	2.69E-04 AM-241 90.3%	8.18E-05 AM-241 90.3%
5.00E+01	2.66E-01 AM-241 90.7%	7.04E-02 AM-241 90.7%	2.55E-02 AM-241 90.7%	9.13E-03 AM-241 90.7%	2.28E-03 AM-241 90.7%	1.22E-03 AM-241 90.7%	7.75E-04 AM-241 90.7%	4.04E-04 AM-241 90.7%	2.52E-04 AM-241 90.7%	7.66E-05 AM-241 90.7%
1.00E+02	2.40E-01 AM-241 91.1%	6.34E-02 AM-241 91.1%	2.30E-02 AM-241 91.1%	8.22E-03 AM-241 91.1%	2.06E-03 AM-241 91.1%	1.10E-03 AM-241 91.1%	6.97E-04 AM-241 91.1%	3.63E-04 AM-241 91.1%	2.26E-04 AM-241 91.1%	6.89E-05 AM-241 91.1%
2.00E+02	1.96E-01 AM-241 91.3%	5.17E-02 AM-241 91.3%	1.87E-02 AM-241 91.3%	6.70E-03 AM-241 91.3%	1.68E-03 AM-241 91.3%	8.95E-04 AM-241 91.3%	5.69E-04 AM-241 91.3%	2.96E-04 AM-241 91.3%	1.85E-04 AM-241 91.3%	5.62E-05 AM-241 91.3%
5.00E+02	1.10E-01 AM-241 88.8%	2.90E-02 AM-241 88.8%	1.05E-02 AM-241 88.8%	3.76E-03 AM-241 88.8%	9.40E-04 AM-241 88.8%	5.02E-04 AM-241 88.8%	3.19E-04 AM-241 88.8%	1.66E-04 AM-241 88.8%	1.04E-04 AM-241 88.8%	3.15E-05 AM-241 88.8%
1.00E+03	4.44E-02 AM-241 79.9%	1.17E-02 AM-241 79.9%	4.26E-03 AM-241 79.9%	1.52E-03 AM-241 79.9%	3.81E-04 AM-241 79.9%	2.03E-04 AM-241 79.9%	1.29E-04 AM-241 79.9%	6.74E-05 AM-241 79.9%	4.20E-05 AM-241 79.9%	1.28E-05 AM-241 79.9%
2.00E+03	9.64E-03 AM-243 51.0%	2.55E-03 AM-243 51.0%	9.23E-04 AM-243 51.0%	3.30E-04 AM-243 51.0%	8.26E-05 AM-243 51.0%	4.41E-05 AM-243 51.0%	2.80E-05 AM-243 51.0%	1.46E-05 AM-243 51.0%	9.10E-06 AM-243 51.0%	2.77E-06 AM-243 51.0%
5.00E+03	8.35E-04 AM-243 98.7%	2.21E-04 AM-243 98.7%	7.99E-05 AM-243 98.7%	2.86E-05 AM-243 98.7%	7.16E-06 AM-243 98.7%	3.82E-06 AM-243 98.7%	2.43E-06 AM-243 98.7%	1.27E-06 AM-243 98.7%	7.88E-07 AM-243 98.7%	2.40E-07 AM-243 98.7%
1.00E+04	4.19E-05 AM-243 100.0%	1.11E-05 AM-243 100.0%	4.01E-06 AM-243 100.0%	1.44E-06 AM-243 100.0%	3.59E-07 AM-243 100.0%	1.92E-07 AM-243 100.0%	1.22E-07 AM-243 100.0%	6.36E-08 AM-243 100.0%	3.96E-08 AM-243 100.0%	1.21E-08 AM-243 100.0%

on repository sealing and drilling occurs 1000 years after sealing. The reason is that americium, which dominates the release, reaches its solubility limit immediately in the small brine pocket. We do not present a table for a 1000-year canister life since if the event time is 1000 years, and the canister life is also 1000 years, the release of a brine pocket to the land surface would bring with it no contamination, since no waste would have escaped the intact canister.

6.2 Effect of No Solubility Limits

In this section we examine the effect of assuming that all nuclides have unlimited solubility, and their entry into groundwater is limited by the leach rate only. Since solubility limits apply to Tc, Np, and Pu (and Am in brine pocket releases), the effects of these nuclides will be greater when there are no solubility limits. The doses from other nuclides do not change.

6.2.1 Release to the aquifer due to drilling

Direct hit on waste

Table 6.9 gives the annual dose rates from a direct hit at 1000 years. It is the same time and event as described in Table 5.7, except for the removal of solubility limits. Tc-99 has replaced Cs-135 as the dominant nuclide up to a dose time of about 50 years. At a dose time of 500 years, Sn-126 has moved 105 meters and is the largest contributor between 0 and 100 meters. Am-241 appears at 20 meters and 1000 years where the dose is 690 rem/yr; the dose rate from the Am-241 is the same in both tables since it is not limited by solubility. Most of the difference in dose rate, about 65 rem/yr, is contributed by plutonium; Sn-126 and Tc-99 are farther downstream. By 5000 years, the Am-241 has decayed enough so that the Am-243 is dominant to about 100 meters. Pu-239 becomes prominent at 10,000 years after the drilling, when the amount of Am-243 has been reduced by decay. In contrast, Table 5.7 shows that Am-243 contributes virtually all of the 10,000-year dose. The presence of Pu-239 in the aquifer makes the contamination last much longer. Comparing the area tables 5.11 and 6.16, we see that the results are nearly the same for about 2000 years.

Table 6.9

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Hits Waste
No Nuclides Limited by Solubility

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	4.09E-03 TC -99 52.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	4.09E-03 TC -99 52.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	4.07E-03 TC -99 52.2%	2.58E-03 TC -99 52.2%	1.83E-03 TC -99 52.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.63E-02 SN-126 84.6%	2.56E-03 TC -99 52.3%	1.82E-03 TC -99 52.3%	1.29E-03 TC -99 52.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.61E-02 SN-126 84.7%	2.53E-03 TC -99 52.4%	1.79E-03 TC -99 52.4%	1.28E-03 TC -99 52.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.52E-02 SN-126 84.7%	1.61E-02 SN-126 84.9%	1.17E-02 SN-126 85.2%	1.23E-03 TC -99 52.7%	7.88E-04 TC -99 52.7%	6.51E-04 TC -99 52.7%	5.71E-04 TC -99 52.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	6.91E+02 AM-241 84.2%	1.53E-02 SN-126 85.0%	1.10E-02 SN-126 85.3%	8.13E-03 SN-126 85.8%	7.41E-04 TC -99 53.3%	6.12E-04 TC -99 53.3%	5.36E-04 TC -99 53.3%	4.49E-04 TC -99 53.3%	3.98E-04 TC -99 53.3%	0.0 NONE 0.0%
2.00E+03	2.08E+02 AM-241 55.8%	1.37E-02 SN-126 85.2%	9.89E-03 SN-126 85.5%	7.29E-03 SN-126 86.0%	6.56E-04 TC -99 54.3%	5.42E-04 TC -99 54.3%	4.75E-04 TC -99 54.3%	3.97E-04 TC -99 54.3%	3.52E-04 TC -99 54.3%	2.74E-04 TC -99 54.3%
5.00E+03	5.56E+01 AM-243 36.0%	4.05E+01 AM-243 36.0%	3.64E+01 AM-243 36.0%	5.27E-03 SN-126 86.4%	3.78E-03 SN-126 87.8%	3.43E-03 SN-126 88.9%	3.31E-03 SN-126 89.9%	2.78E-04 TC -99 56.8%	2.47E-04 TC -99 56.8%	1.92E-04 TC -99 56.8%
1.00E+04	2.36E+01 PU-239 36.8%	1.72E+01 PU-239 36.8%	1.54E+01 PU-239 36.8%	1.75E+01 PU-239 36.8%	2.21E-03 SN-126 88.2%	2.00E-03 SN-126 89.2%	1.93E-03 SN-126 90.2%	1.97E-03 SN-126 92.0%	2.13E-03 SN-126 93.4%	1.09E-04 TC -99 59.6%

Penetration into contaminated repository water

Table 6.10 gives the annual dose rates from drinking aquifer water after a drill penetrates a contaminated granite strata (granite tank) when there are no solubility limits. Table 5.17 gives the results for this event with solubility limits. Tc-99 dominates the early portion in Table 6.10, as compared to Cs-135 in the solubility-limited case. The early dose rates in Table 6.10 are about a factor of two higher than those in Table 5.17; at 50 years the maximum dose rate (Table 6.10) is about 0.02 rem/yr. Between 100 and 500 years, Sn-126 is the dominant nuclide while Tc-99 is more important downstream beyond the Sn-126. Am-241 is dominant from 1000 to 2000 years. The annual dose rates for these times in Table 6.10 are higher than those in Table 5.17 because of some contribution from Pu-239. At 5000 years, Am-243 contributes about 36% of the total of 2000 rem/yr or 720 rem/yr. At 5000 years with solubility limits, the 131 rem/yr from the Am-243 is 95.5% of the total 137 rem/yr. The additional 1850 rem/yr in Table 6.10 is the contribution of solubility-limited nuclides, especially plutonium nuclides. At 10,000 years, Pu-239 is the dominate nuclide in Table 6.10, compared to Am-243 in the base case. At the 10,000-year dose time, the Pu-239 provides a maximum dose of 2000 rem/yr.

Tables 5.21 and 6.16 give the areas contaminated by the release with and without solubility limits. The areas contaminated are about the same for both cases until 10,000 years, when they are slightly larger without solubility limits than with solubility limits. The lack of solubility limits increases the time for potential contamination.

Tables 5.12 and 6.11 give results for drilling releases from a brine pocket to the aquifers. In Table 5.12 some nuclides are solubility-limited, however, in Table 6.11, they are leach-limited. The annual dose rates for brine pocket releases in Table 6.11 are somewhat smaller than those for granite tank releases in Table 6.10; the maximum dose rate in Table 6.10 is about 4000 rem/yr whereas in Table 6.11 it is near 1300 rem/yr and in Table 5.12 it is 1100 rem/yr.

Table 6.10

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
No Nuclides Limited By Solubility

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.23E-02 TC -99 52.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	2.27E-02 TC -99 52.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	2.37E-02 TC -99 52.2%	1.47E-02 TC -99 52.2%	1.00E-02 TC -99 52.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.48E-01 SN-126 82.8%	1.58E-02 TC -99 52.3%	1.08E-02 TC -99 52.3%	7.09E-03 TC -99 52.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.70E-01 SN-126 83.1%	1.78E-02 TC -99 52.4%	1.23E-02 TC -99 52.4%	8.18E-03 TC -99 52.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.29E-01 SN-126 83.7%	1.30E-01 SN-126 82.1%	7.25E-02 SN-126 77.6%	1.10E-02 TC -99 52.7%	6.14E-03 TC -99 52.7%	4.40E-03 TC -99 52.7%	3.24E-03 TC -99 52.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	4.07E+03 AM-241 84.2%	1.85E-01 SN-126 83.3%	1.15E-01 SN-126 81.2%	5.61E-02 SN-126 73.3%	8.77E-03 TC -99 53.3%	6.68E-03 TC -99 53.3%	5.34E-03 TC -99 53.3%	3.59E-03 TC -99 53.3%	2.34E-03 TC -99 53.3%	0.0 NONE 0.0%
2.00E+03	2.92E+03 AM-241 55.8%	2.69E-01 SN-126 84.2%	1.79E-01 SN-126 83.3%	1.09E-01 SN-126 80.8%	1.27E-02 TC -99 54.3%	1.00E-02 TC -99 54.3%	8.37E-03 TC -99 54.3%	6.29E-03 TC -99 54.3%	4.94E-03 TC -99 54.3%	1.73E-03 TC -99 54.3%
5.00E+03	2.04E+03 AM-243 36.0%	1.04E+03 AM-243 36.0%	2.76E+02 AM-243 35.9%	1.99E-01 SN-126 84.2%	1.05E-01 SN-126 81.3%	6.74E-02 SN-126 76.5%	3.61E-02 SN-126 62.5%	1.08E-02 TC -99 56.8%	9.08E-03 TC -99 56.8%	5.64E-03 TC -99 56.8%
1.00E+04	2.07E+03 PU-239 36.8%	1.21E+03 PU-239 36.8%	7.22E+02 PU-239 36.8%	1.68E+02 PU-239 36.7%	1.63E-01 SN-126 84.3%	1.24E-01 SN-126 83.4%	9.95E-02 SN-126 82.1%	6.42E-02 SN-126 77.6%	3.13E-02 SN-126 60.7%	8.29E-03 TC -99 59.6%

Table 6.11

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
No Nuclides Limited by Solubility

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	7.45E-03 TC -99 52.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	7.50E-03 TC -99 52.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	7.48E-03 TC -99 52.2%	4.73E-03 TC -99 52.2%	3.35E-03 TC -99 52.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	4.83E-02 SN-126 84.6%	4.70E-03 TC -99 52.3%	3.33E-03 TC -99 52.3%	2.37E-03 TC -99 52.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	4.78E-02 SN-126 84.7%	4.63E-03 TC -99 52.4%	3.29E-03 TC -99 52.4%	2.34E-03 TC -99 52.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	4.62E-02 SN-126 84.7%	2.96E-02 SN-126 84.9%	2.14E-02 SN-126 85.2%	2.25E-03 TC -99 52.7%	1.45E-03 TC -99 52.7%	1.19E-03 TC -99 52.7%	1.05E-03 TC -99 52.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.27E+03 AM-241 84.2%	2.80E-02 SN-126 85.0%	2.02E-02 SN-126 85.3%	1.49E-02 SN-126 85.8%	1.36E-03 TC -99 53.3%	1.12E-03 TC -99 53.3%	9.84E-04 TC -99 53.3%	8.22E-04 TC -99 53.3%	7.29E-04 TC -99 53.3%	0.0 NONE 0.0%
2.00E+03	3.81E+02 AM-241 55.8%	2.51E-02 SN-126 85.1%	1.81E-02 SN-126 85.3%	1.34E-02 SN-126 85.9%	1.20E-03 TC -99 54.3%	9.91E-04 TC -99 54.3%	8.68E-04 TC -99 54.3%	7.27E-04 TC -99 54.3%	6.46E-04 TC -99 54.3%	5.02E-04 TC -99 54.3%
5.00E+03	1.01E+02 AM-243 36.0%	7.42E+01 AM-243 36.0%	6.66E+01 AM-243 36.0%	9.56E-03 SN-126 86.3%	6.91E-03 SN-126 87.9%	6.29E-03 SN-126 89.1%	6.06E-03 SN-126 90.0%	5.05E-04 TC -99 56.8%	4.48E-04 TC -99 56.8%	3.52E-04 TC -99 56.8%
1.00E+04	4.27E+01 PU-239 36.8%	3.16E+01 PU-239 36.8%	2.79E+01 PU-239 36.8%	3.21E+01 PU-239 36.8%	4.05E-03 SN-126 88.2%	3.64E-03 SN-126 89.2%	3.50E-03 SN-126 90.2%	3.61E-03 SN-126 92.1%	3.89E-03 SN-126 93.5%	1.99E-04 TC -99 59.6%

Once again Tc-99 and Sn-126 are the dominant nuclides at all distances until 1000 years after the drilling occurred. We then see the americium isotopes dominating the closer distances (up to 100 m) until Pu-239 takes precedence at 10,000 years and up to 200 m. This is the same pattern followed in Table 5.12 except that Am-243 maintains dominance at 10,000 years.

6.2.2 Release to the aquifer due to faulting

Direct hit on waste

Table 6.12 shows the results of a fault line through waste from, or in, a row of waste canisters without solubility limits on the nuclides. The comparable data with solubility limits are in Table 5.22. The same nuclides, Sn-126, Am-241, and Am-243, dominate until a dose time of 10,000 years when Pu-239 has replaced Am-243 as the major contributor to the total dose rate. The peak dose rates in Tables 5.22 and 6.12 are near 600 rem/yr and both occur 500 years after the event. Furthermore, other values in the tables are similar--which implies that the presence or absence of solubility limits does not affect releases in this scenario.

Granite tank

The results of the faulting event are presented in Table 6.13; the same event with solubility limits is given in Table 5.26. In the first 20 years after the event, Sn-126 is the dominant isotope and the annual dose rates are almost two times higher. Am-241 dominates both tables from 50 years through 2000 years. The dose rates, assuming no solubility limits, converge with those with solubility limits until 5000 years. At 5000 years, Am-243 dominates the entire length studied but other nuclides, particularly plutonium isotopes, also contribute significantly. At 10,000 years, Pu-239 dominates both tables when the americium isotopes have decayed to lower levels. The removal of the solubility limits in this scenario has increased the annual dose rates by, at most, a factor of two.

Table 6.12

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Waste Directly Affected
No Nuclides Limited by Solubility

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	5.41E-03 SN-126 41.4%	5.51E-03 SN-126 40.6%	5.51E-03 SN-126 40.6%	5.51E-03 SN-126 40.6%	5.51E-03 SN-126 40.6%	5.51E-03 SN-126 40.6%	5.51E-03 SN-126 40.6%	5.51E-03 SN-126 40.6%	5.51E-03 SN-126 40.6%	5.51E-03 SN-126 40.6%
2.00E+01	8.39E-03 SN-126 62.2%	1.02E-02 SN-126 51.0%	1.02E-02 SN-126 51.0%	1.02E-02 SN-126 51.0%	1.02E-02 SN-126 51.0%	1.02E-02 SN-126 51.0%	1.02E-02 SN-126 51.0%	1.02E-02 SN-126 51.0%	1.02E-02 SN-126 51.0%	1.02E-02 SN-126 51.0%
5.00E+01	1.41E+01 AM-241 95.3%	1.41E+01 AM-241 95.3%	1.41E+01 AM-241 95.3%	1.41E+01 AM-241 95.3%	1.41E+01 AM-241 95.3%	1.41E+01 AM-241 95.3%	1.41E+01 AM-241 95.3%	1.41E+01 AM-241 95.3%	1.41E+01 AM-241 95.3%	1.41E+01 AM-241 95.3%
1.00E+02	2.37E+02 AM-241 95.1%	2.37E+02 AM-241 95.1%	2.37E+02 AM-241 95.1%	2.37E+02 AM-241 95.1%	2.37E+02 AM-241 95.1%	2.37E+02 AM-241 95.1%	2.37E+02 AM-241 95.1%	2.37E+02 AM-241 95.1%	2.37E+02 AM-241 95.1%	2.37E+02 AM-241 95.1%
2.00E+02	4.72E+02 AM-241 94.4%	4.73E+02 AM-241 94.4%	4.73E+02 AM-241 94.4%	4.73E+02 AM-241 94.4%	4.73E+02 AM-241 94.4%	4.73E+02 AM-241 94.4%	4.73E+02 AM-241 94.4%	4.73E+02 AM-241 94.4%	4.73E+02 AM-241 94.4%	4.73E+02 AM-241 94.4%
5.00E+02	6.33E+02 AM-241 91.6%	6.33E+02 AM-241 91.6%	6.33E+02 AM-241 91.6%	6.33E+02 AM-241 91.6%	6.33E+02 AM-241 91.6%	6.33E+02 AM-241 91.6%	6.33E+02 AM-241 91.6%	6.33E+02 AM-241 91.6%	6.33E+02 AM-241 91.6%	6.33E+02 AM-241 91.6%
1.00E+03	4.69E+02 AM-241 84.2%	4.83E+02 AM-241 84.2%	4.83E+02 AM-241 84.2%	4.83E+02 AM-241 84.2%	4.83E+02 AM-241 84.2%	4.83E+02 AM-241 84.2%	4.83E+02 AM-241 84.2%	4.83E+02 AM-241 84.2%	4.83E+02 AM-241 84.2%	4.83E+02 AM-241 84.2%
2.00E+03	1.41E+02 AM-241 55.8%	2.15E+02 AM-241 55.8%	2.15E+02 AM-241 55.8%	2.15E+02 AM-241 55.8%	2.15E+02 AM-241 55.8%	2.15E+02 AM-241 55.8%	2.15E+02 AM-241 55.8%	2.15E+02 AM-241 55.8%	2.15E+02 AM-241 55.8%	2.15E+02 AM-241 55.8%
5.00E+03	3.77E+01 AM-243 36.0%	6.27E+01 AM-243 36.0%	8.61E+01 AM-243 36.0%	8.78E+01 AM-243 35.9%	8.79E+01 AM-243 35.9%	8.79E+01 AM-243 35.9%	8.79E+01 AM-243 35.9%	8.79E+01 AM-243 35.9%	8.79E+01 AM-243 35.9%	8.79E+01 AM-243 35.9%
1.00E+04	1.60E+01 PU-239 36.8%	2.66E+01 PU-239 36.8%	3.65E+01 PU-239 36.8%	4.65E+01 PU-239 36.8%	4.71E+01 PU-239 36.8%	4.71E+01 PU-239 36.8%	4.71E+01 PU-239 36.8%	4.71E+01 PU-239 36.8%	4.71E+01 PU-239 36.7%	4.71E+01 PU-239 36.7%

Table 6.13

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement in GRANITE
1000 Years After Repository Sealing

Repository Water Affected
No Nuclides Limited by Solubility

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	6.61E+01 SN-126 53.9%	6.86E+01 SN-126 51.9%	6.86E+01 SN-126 51.9%	6.86E+01 SN-126 51.9%	6.86E+01 SN-126 51.9%	6.86E+01 SN-126 51.9%	6.86E+01 SN-126 51.9%	6.86E+01 SN-126 51.9%	6.86E+01 SN-126 51.9%	6.86E+01 SN-126 51.9%
2.00E+01	4.38E+01 SN-126 88.6%	6.33E+01 SN-126 61.2%	6.33E+01 SN-126 61.2%	6.33E+01 SN-126 61.2%	6.33E+01 SN-126 61.2%	6.33E+01 SN-126 61.2%	6.33E+01 SN-126 61.2%	6.33E+01 SN-126 61.2%	6.33E+01 SN-126 61.2%	6.33E+01 SN-126 61.2%
5.00E+01	2.95E+05 AM-241 95.4%	2.95E+05 AM-241 95.4%	2.95E+05 AM-241 95.4%	2.95E+05 AM-241 95.4%	2.95E+05 AM-241 95.4%	2.95E+05 AM-241 95.4%	2.95E+05 AM-241 95.4%	2.95E+05 AM-241 95.4%	2.95E+05 AM-241 95.4%	2.95E+05 AM-241 95.4%
1.00E+02	5.75E+05 AM-241 95.1%	5.75E+05 AM-241 95.1%	5.75E+05 AM-241 95.1%	5.75E+05 AM-241 95.1%	5.75E+05 AM-241 95.1%	5.75E+05 AM-241 95.1%	5.75E+05 AM-241 95.1%	5.75E+05 AM-241 95.1%	5.75E+05 AM-241 95.1%	5.75E+05 AM-241 95.1%
2.00E+02	3.96E+05 AM-241 94.4%	3.96E+05 AM-241 94.4%	3.96E+05 AM-241 94.4%	3.96E+05 AM-241 94.4%	3.96E+05 AM-241 94.4%	3.96E+05 AM-241 94.4%	3.96E+05 AM-241 94.4%	3.96E+05 AM-241 94.4%	3.96E+05 AM-241 94.4%	3.96E+05 AM-241 94.4%
5.00E+02	2.30E+05 AM-241 91.6%	2.30E+05 AM-241 91.6%	2.30E+05 AM-241 91.6%	2.30E+05 AM-241 91.6%	2.30E+05 AM-241 91.6%	2.30E+05 AM-241 91.6%	2.30E+05 AM-241 91.6%	2.30E+05 AM-241 91.6%	2.30E+05 AM-241 91.6%	2.30E+05 AM-241 91.6%
1.00E+03	7.34E+04 AM-241 84.2%	1.24E+05 AM-241 84.2%	1.24E+05 AM-241 84.2%	1.24E+05 AM-241 84.2%	1.24E+05 AM-241 84.2%	1.24E+05 AM-241 84.2%	1.24E+05 AM-241 84.2%	1.24E+05 AM-241 84.2%	1.24E+05 AM-241 84.2%	1.24E+05 AM-241 84.2%
2.00E+03	2.21E+04 AM-241 55.8%	4.76E+04 AM-241 55.8%	4.76E+04 AM-241 55.8%	4.76E+04 AM-241 55.8%	4.76E+04 AM-241 55.8%	4.76E+04 AM-241 55.8%	4.76E+04 AM-241 55.8%	4.76E+04 AM-241 55.8%	4.76E+04 AM-241 55.8%	4.76E+04 AM-241 55.8%
5.00E+03	5.90E+03 AM-243 36.0%	1.09E+04 AM-243 36.0%	1.76E+04 AM-243 36.0%	2.08E+04 AM-243 36.0%	2.08E+04 AM-243 35.9%	2.08E+04 AM-243 35.9%	2.09E+04 AM-243 35.9%	2.09E+04 AM-243 35.9%	2.09E+04 AM-243 35.9%	2.09E+04 AM-243 35.9%
1.00E+04	2.50E+03 PU-239 36.8%	4.62E+03 PU-239 36.8%	7.48E+03 PU-239 36.8%	1.33E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%	1.51E+04 PU-239 36.8%

6.2.3 Release to the land surface

Table 6.14 gives the annual dose rates resulting from breathing air contaminated by release to the land surface from a drill puncturing a brine pocket around two canisters, assuming no solubility limits. The doses in Table 6.14 are much higher than those for the similar case with solubility limits (Table 5.34), the highest being 22 rem/yr compared with 0.02 rem/yr in the base case. There are two reasons for this increase. First, the annual dose rates from Am-241, are larger by a factor of about 20 because americium solubility is limiting in the base case. Second, other nuclides, such as plutonium isotopes and technetium, which are solubility-limited in the base case, are released here. After 1000 years, Pu-239 and -240 dominate the doses. Areas contaminated above 0.5 rem/yr are presented on Table 6.16; they are all less then one ha. In the base case, there were only small areas above 0.5 rem/year.

6.2.4 Release to the aquifer due to shaft seal leakage

The annual dose rates in Table 6.15 and the contaminated areas (refer to direct hit drilling in Table 6.16) are about the same as those of Tables 5.41 and 5.42, respectively. The removal of the solubility limits has caused the annual dose rates in Table 6.15 to increase only slightly above those of Table 5.41. The contaminated areas in the base case are about the same.

6.3 Effect of Varying the Leach Rate

The base case assumed a leach rate of 10^{-4} yr^{-1}. In this chapter, we examine the effect of varying this leach rate. Values examined range from 10^{-5} yr^{-1} to 10^{-2} yr^{-1}. A higher leach rate would cause radionuclides (except those whose concentrations are limited by solubility) to enter the environment more quickly, and dose rates from them would be higher. This would be true for all releases from brine pockets and from the granite tank water, except for direct hit releases to the land surface. Since rapid leaching would deplete

Table 6.14

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
No Nuclides Limited By Solubility

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.21E+01 AM-241 53.9%	5.84E+00 AM-241 53.9%	2.11E+00 AM-241 53.9%	7.57E-01 AM-241 53.9%	1.89E-01 AM-241 53.9%	1.01E-01 AM-241 53.9%	6.42E-02 AM-241 53.9%	3.35E-02 AM-241 53.9%	2.09E-02 AM-241 53.9%	6.35E-03 AM-241 53.9%
2.00E+01	2.18E+01 AM-241 53.5%	5.76E+00 AM-241 53.5%	2.09E+00 AM-241 53.5%	7.46E-01 AM-241 53.5%	1.87E-01 AM-241 53.5%	9.96E-02 AM-241 53.5%	6.33E-02 AM-241 53.5%	3.30E-02 AM-241 53.5%	2.06E-02 AM-241 53.5%	6.26E-03 AM-241 53.5%
5.00E+01	2.09E+01 AM-241 52.5%	5.53E+00 AM-241 52.5%	2.00E+00 AM-241 52.5%	7.17E-01 AM-241 52.5%	1.79E-01 AM-241 52.5%	9.57E-02 AM-241 52.5%	6.08E-02 AM-241 52.5%	3.17E-02 AM-241 52.5%	1.98E-02 AM-241 52.5%	6.01E-03 AM-241 52.5%
1.00E+02	1.96E+01 AM-241 50.7%	5.17E+00 AM-241 50.7%	1.87E+00 AM-241 50.7%	6.71E-01 AM-241 50.7%	1.68E-01 AM-241 50.7%	8.95E-02 AM-241 50.7%	5.69E-02 AM-241 50.7%	2.97E-02 AM-241 50.7%	1.85E-02 AM-241 50.7%	5.63E-03 AM-241 50.7%
2.00E+02	1.72E+01 AM-241 47.1%	4.55E+00 AM-241 47.1%	1.65E+00 AM-241 47.1%	5.90E-01 AM-241 47.1%	1.48E-01 AM-241 47.1%	7.88E-02 AM-241 47.1%	5.01E-02 AM-241 47.1%	2.61E-02 AM-241 47.1%	1.63E-02 AM-241 47.1%	4.95E-03 AM-241 47.1%
5.00E+02	1.21E+01 AM-241 36.6%	3.19E+00 AM-241 36.6%	1.16E+00 AM-241 36.6%	4.14E-01 AM-241 36.6%	1.04E-01 AM-241 36.6%	5.53E-02 AM-241 36.6%	3.51E-02 AM-241 36.6%	1.83E-02 AM-241 36.6%	1.14E-02 AM-241 36.6%	3.47E-03 AM-241 36.6%
1.00E+03	7.36E+00 PU-240 43.4%	1.94E+00 PU-240 43.4%	7.04E-01 PU-240 43.4%	2.52E-01 PU-240 43.4%	6.31E-02 PU-240 43.4%	3.37E-02 PU-240 43.4%	2.14E-02 PU-240 43.4%	1.12E-02 PU-240 43.4%	6.95E-03 PU-240 43.4%	2.11E-03 PU-240 43.4%
2.00E+03	3.44E+00 PU-240 50.5%	9.10E-01 PU-240 50.5%	3.30E-01 PU-240 50.5%	1.18E-01 PU-240 50.5%	2.95E-02 PU-240 50.5%	1.58E-02 PU-240 50.5%	1.00E-02 PU-240 50.5%	5.22E-03 PU-240 50.5%	3.25E-03 PU-240 50.5%	9.90E-04 PU-240 50.5%
5.00E+03	5.80E-01 PU-239 49.3%	1.53E-01 PU-239 49.3%	5.55E-02 PU-239 49.3%	1.99E-02 PU-239 49.3%	4.97E-03 PU-239 49.3%	2.65E-03 PU-239 49.3%	1.69E-03 PU-239 49.3%	8.79E-04 PU-239 49.3%	5.48E-04 PU-239 49.3%	1.67E-04 PU-239 49.3%
1.00E+04	3.40E-02 PU-239 58.3%	8.98E-03 PU-239 58.3%	3.25E-03 PU-239 58.3%	1.16E-03 PU-239 58.3%	2.91E-04 PU-239 58.3%	1.55E-04 PU-239 58.3%	9.88E-05 PU-239 58.3%	5.15E-05 PU-239 58.3%	3.21E-05 PU-239 58.3%	9.77E-06 PU-239 58.3%

Table 6.15

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Shaft Seal Leakage in GRANITE

No Nuclides Limited by Solubility

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	8.50E-06 SR -90 67.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	2.89E-04 SR -90 66.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.40E-03 SR -90 62.0%	4.16E-04 SR -90 62.0%	9.34E-06 SR -90 62.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.34E-03 SR -90 47.4%	1.07E-03 SR -90 48.1%	3.84E-04 SR -90 48.1%	6.09E-06 SR -90 48.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	8.32E-03 SN-126 60.2%	1.82E-03 TC -99 42.8%	9.90E-04 TC -99 42.8%	3.54E-04 TC -99 42.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	6.92E-02 SN-126 79.9%	2.49E-02 SN-126 66.3%	5.62E-03 TC -99 50.7%	3.20E-03 TC -99 52.2%	9.57E-04 TC -99 52.2%	2.64E-04 TC -99 52.2%	9.31E-06 TC -99 52.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	7.32E+01 AM-241 91.3%	1.21E-01 SN-126 79.2%	5.49E-02 SN-126 68.7%	1.16E-02 TC -99 51.0%	5.52E-03 TC -99 52.7%	3.47E-03 TC -99 52.7%	2.17E-03 TC -99 52.7%	6.36E-04 TC -99 52.7%	2.17E-05 TC -99 52.7%	0.0 NONE 0.0%
2.00E+03	4.14E+03 AM-241 72.1%	3.64E-01 SN-126 83.0%	2.21E-01 SN-126 80.5%	1.06E-01 SN-126 71.9%	1.71E-02 TC -99 53.8%	1.28E-02 TC -99 53.8%	1.01E-02 TC -99 53.8%	6.58E-03 TC -99 53.8%	4.30E-03 TC -99 53.8%	5.26E-05 TC -99 53.8%
5.00E+03	4.14E+03 AM-243 35.7%	1.86E+03 AM-243 35.7%	3.93E+01 AM-243 35.2%	3.82E-01 SN-126 84.3%	1.83E-01 SN-126 79.4%	8.91E-02 SN-126 65.8%	2.92E-02 TC -99 50.6%	2.09E-02 TC -99 56.4%	1.76E-02 TC -99 56.4%	1.03E-02 TC -99 56.4%
1.00E+04	2.39E+03 PU-239 36.1%	1.78E+03 PU-239 36.1%	1.38E+03 PU-239 36.1%	6.19E+01 PU-239 36.0%	2.20E-01 SN-126 88.6%	1.94E-01 SN-126 89.3%	1.70E-01 SN-126 89.2%	1.03E-01 SN-126 85.0%	2.06E-02 TC -99 39.9%	1.10E-02 TC -99 59.4%

Table 6.16

Area (ha*) of the Aquifer Contaminated
Above the Specified Dose Rate Levels
Because of Drilling 1000 Years after Sealing

No solubility limits

Event description	Length of time after event (yr)	Dose Rate Levels (rem/yr)			
		0.5	5	50	500
Direct hit on waste	0-500	0	0	0	0
	1000	0.33	0.28	0.20	0.07
	2000	0.31	0.24	0.15	0
	5000	2.37	1.63	0.04	0
	10000	7.35	4.35	0	0
Brine pocket to surface	10	0.65	0	0	0
	20	0.64	0	0	0
	50	0.62	0	0	0
	100	0.59	0	0	0
	200	0.53	0	0	0
	500	0.34	0	0	0
	1000-10000	0	0	0	0
Granite tank to aquifer	0-500	0	0	0	0
	1000	0.36	0.30	0.24	0.15
	2000	0.34	0.29	0.22	0.11
	5000	2.74	2.13	1.25	0
	10000	8.78	6.47	2.59	0
Brine pocket to aquifer	0-500	0	0	0	0
	1000	0.35	0.29	0.22	0.12
	2000	0.32	0.26	0.18	0
	5000	2.53	1.85	0.67	0
	10000	7.96	5.30	0	0

*1 hectare (ha) = 10^4 square meters

NOTE: Shaft seal release are very similar to direct hit drilling.

the nuclide inventory available to groundwater, we would expect that the dose rates at higher leach rates would fall off more rapidly as the dose times increase.

6.3.1 Release to the aquifer due to drilling

Direct hit on waste

Tables 6.17, 6.18 and 6.19 show the annual dose rates from drinking aquifer water after a direct hit on waste with leach rates of 10^{-2}, 10^{-3} and 10^{-5} yr^{-1}, respectively. Together with Table 5.7, they show the effect of a changing leach rate upon the results of this event. For the first 100 years after the event, the dose rate varies linearly with the leach rate. However, as dose times increase and waste inventory is depleted by leaching, the dose rates deviate from linearity. For example, after 500 years, with a leach rate of 10^{-2}, over 99% of the available waste has been removed (ignoring radioactive decay). This is reflected in the sharp drop in the annual dose rates after 1000 years for a leach rate of 10^{-2}, and after 5000 years for a leach rate of 10^{-3}. The rapid depletion of the inventory produces a very small band of contamination for isotopes with retardation factors of 100. All the americium, for instance, that is leached in 500 years is in a band only as wide as the distance it travels in 500 years, 10.5 meters. The corresponding bands for nuclides with retardation factors of 10 and 1 are 105 meters and 1050 meters wide. Since Am-241 and -243 are dominant and have retardation factors of 100, their contribution to the dose rate is limited to time and distance such that distance equals approximately 0.021 times dose time.

Cs-135 and Sn-126 are dominant for dose times less than 1000 years. At 1000 years, americium appears in all cases because nuclide movement in the aquifer does not depend on leach rate. The dose rates in Table 6.17 reach a high of 39,000 rem/yr at 1000 years and 20 meters, and then fall off very quickly. The maximum annual dose rate would actually be calculated at 21 meters due to the high leach rate. The 5000-year dose time shows a significant dose at 100 meters,

Table 6.17

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Hits Waste
Leach Rate = 10^{-2} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.95E-01 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.76E-01 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.30E-01 CS-135 58.8%	9.51E-02 CS-135 58.8%	8.53E-02 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.21E+00 SN-126 96.4%	5.75E-02 CS-135 58.9%	5.16E-02 CS-135 58.9%	5.88E-02 CS-135 58.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	8.11E-01 SN-126 96.4%	2.11E-02 CS-135 59.2%	1.89E-02 CS-135 59.2%	2.15E-02 CS-135 59.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	4.03E-02 SN-126 96.5%	1.04E-01 SN-126 99.0%	7.85E-01 SN-126 99.9%	1.06E-03 CS-135 60.0%	2.79E-03 CS-135 60.1%	7.48E-03 CS-135 60.1%	2.13E-02 CS-135 60.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	3.90E+04 AM-241 93.1%	6.99E-04 SN-126 98.5%	5.27E-03 SN-126 99.8%	4.36E-01 SN-126 100.0%	1.95E-05 CS-135 58.0%	5.02E-05 CS-135 60.4%	1.41E-04 CS-135 61.1%	1.24E-03 CS-135 61.5%	1.16E-02 CS-135 61.5%	0.0 NONE 0.0%
2.00E+03	5.18E-01 AM-241 70.0%	3.17E-08 SN-126 98.0%	2.38E-07 SN-126 99.8%	1.96E-05 SN-126 100.0%	1.74E-09 TC -99 54.3%	4.68E-09 TC -99 54.3%	1.33E-08 TC -99 54.3%	1.18E-07 TC -99 54.3%	1.03E-06 TC -99 51.1%	4.88E-03 CS-135 64.2%
5.00E+03	2.20E-14 AM-243 36.0%	2.22E-08 AM-243 36.0%	1.30E+02 AM-243 95.6%	1.80E-18 SN-126 100.0%	1.82E-12 SN-126 100.0%	2.20E-07 SN-126 100.0%	2.82E-02 SN-126 100.0%	1.04E-20 TC -99 56.8%	9.76E-20 TC -99 56.8%	9.44E-16 TC -99 56.8%
1.00E+04	2.96E-36 PU-239 36.8%	3.00E-30 PU-239 36.8%	4.64E-20 PU-239 36.8%	5.16E+00 AM-243 99.8%	3.39E-34 SN-126 100.0%	4.10E-29 SN-126 100.0%	5.25E-24 SN-126 100.0%	9.39E-14 SN-126 100.0%	1.78E-03 SN-126 100.0%	1.71E-37 TC -99 59.6%

Table 6.18

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Bits Waste
Leach Rate = 10^{-3} per year

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.96E-02 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.94E-02 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.88E-02 CS-135 58.8%	1.20E-02 CS-135 58.8%	8.72E-03 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.40E-01 SN-126 92.6%	1.14E-02 CS-135 58.9%	8.27E-03 CS-135 58.9%	6.14E-03 CS-135 58.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.17E-01 SN-126 92.6%	1.03E-02 CS-135 59.2%	7.45E-03 CS-135 59.2%	5.53E-03 CS-135 59.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.60E-01 SN-126 92.7%	1.16E-01 SN-126 93.5%	1.03E-01 SN-126 94.7%	4.04E-03 CS-135 60.1%	2.94E-03 CS-135 60.1%	2.71E-03 CS-135 60.1%	2.64E-03 CS-135 60.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	5.98E+03 AM-241 93.1%	6.99E-02 SN-126 93.6%	6.20E-02 SN-126 94.8%	6.92E-02 SN-126 96.5%	1.74E-03 CS-135 61.4%	1.60E-03 CS-135 61.5%	1.57E-03 CS-135 61.5%	1.62E-03 CS-135 61.5%	1.78E-03 CS-135 61.5%	0.0 NONE 0.0%
2.00E+03	5.89E+02 AM-241 76.6%	2.55E-02 SN-126 93.8%	2.26E-02 SN-126 95.0%	2.53E-02 SN-126 96.7%	6.15E-04 CS-135 64.1%	5.65E-04 CS-135 64.1%	5.52E-04 CS-135 64.2%	5.71E-04 CS-135 64.2%	6.28E-04 CS-135 64.2%	1.15E-03 CS-135 64.2%
5.00E+03	5.51E+00 AM-243 95.0%	1.45E+01 AM-243 95.5%	1.10E+02 AM-243 95.6%	1.23E-03 SN-126 96.9%	3.17E-03 SN-126 99.1%	8.47E-03 SN-126 99.7%	2.41E-02 SN-126 99.9%	2.58E-05 CS-135 70.6%	2.83E-05 CS-135 70.8%	5.14E-05 CS-135 71.4%
1.00E+04	4.76E-02 AM-243 47.1%	7.62E-02 AM-243 77.6%	4.63E-01 AM-243 97.7%	3.74E+01 AM-243 100.0%	2.09E-05 SN-126 98.1%	5.53E-05 SN-126 99.3%	1.57E-04 SN-126 99.8%	1.38E-03 SN-126 100.0%	1.29E-02 SN-126 100.0%	5.49E-07 CS-135 45.0%

Table 6.19

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Hits Waste
Leach Rate = 10^{-5} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.03E-04 CS-135 56.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	2.02E-04 CS-135 56.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	2.02E-04 CS-135 56.9%	1.28E-04 CS-135 56.9%	9.04E-05 CS-135 56.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.43E-03 SN-126 91.7%	1.27E-04 CS-135 57.0%	9.01E-05 CS-135 57.0%	6.37E-05 CS-135 57.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.43E-03 SN-126 91.8%	1.26E-04 CS-135 57.3%	8.95E-05 CS-135 57.3%	6.33E-05 CS-135 57.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.41E-03 SN-126 91.9%	1.53E-03 SN-126 91.9%	1.08E-03 SN-126 91.9%	6.21E-05 CS-135 58.3%	3.94E-05 CS-135 58.2%	3.22E-05 CS-135 58.1%	2.80E-05 CS-135 58.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	6.28E+01 AM-241 93.1%	1.51E-03 SN-126 92.0%	1.07E-03 SN-126 92.1%	7.61E-04 SN-126 92.1%	3.82E-05 CS-135 59.7%	3.12E-05 CS-135 59.7%	2.71E-05 CS-135 59.6%	2.22E-05 CS-135 59.5%	1.93E-05 CS-135 59.4%	0.0 NONE 0.0%
2.00E+03	1.67E+01 AM-241 76.4%	1.48E-03 SN-126 92.3%	1.05E-03 SN-126 92.3%	7.46E-04 SN-126 92.4%	3.61E-05 CS-135 62.5%	2.95E-05 CS-135 62.5%	2.56E-05 CS-135 62.5%	2.10E-05 CS-135 62.4%	1.82E-05 CS-135 62.4%	1.31E-05 CS-135 62.0%
5.00E+03	3.04E+00 AM-243 94.5%	1.95E+00 AM-243 94.5%	1.42E+00 AM-243 94.3%	7.04E-04 SN-126 93.0%	4.51E-04 SN-126 93.1%	3.73E-04 SN-126 93.1%	3.26E-04 SN-126 93.2%	1.81E-05 CS-135 70.0%	1.57E-05 CS-135 70.0%	1.13E-05 CS-135 69.9%
1.00E+04	1.77E+00 AM-243 98.2%	1.13E+00 AM-243 98.4%	8.20E-01 AM-243 98.6%	6.08E-01 AM-243 98.5%	4.12E-04 SN-126 93.7%	3.40E-04 SN-126 93.7%	2.98E-04 SN-126 93.8%	2.49E-04 SN-126 93.9%	2.20E-04 SN-126 94.0%	9.37E-06 CS-135 79.7%

Table 6.20

Area (ha*) of the Aquifer Contaminated
Above the Specified Dose Rate Levels
Following a Direct Drilling Hit on Waste
1000 Years after Sealing

Variable leach rates

Leach Rate (per year)	Length of time after event (yr)	Dose Rate Levels (rem/yr) 0.5	5	50	500	5000
10^{-2}	0-50	0	0	0	0	0
	100	0.15	0	0	0	0
	200	0.09	0	0	0	0
	500	0.49	0	0	0	0
	1000	0.42	0.37	0.32	0.26	0.18
	2000	0.02	0	0	0	0
	5000	1.73	1.33	0.72	0	0
	10000	4.23	0.48	0	0	0
10^{-3}	0-500	0	0	0	0	0
	1000	0.38	0.33	0.27	0.20	0.05
	2000	0.33	0.27	0.20	0.05	0
	5000	2.41	1.62	0.65	0	0
	10000	5.76	3.93	0	0	0
10^{-4}	0-500	0	0	0	0	0
	1000	0.33	0.27	0.20	0.06	0
	2000	0.30	0.23	0.13	0	0
	5000	2.10	1.20	0	0	0
	10000	6.11	1.26	0	0	0
10^{-5}	0-500	0	0	0	0	0
	1000	0.27	0.20	0.06	0	0
	2000	0.23	0.14	0	0	0
	5000	1.24	0	0	0	0
	10000	0.07	0	0	0	0

*1 hectare (ha) = 10^4 square meters

which is within the 105-meter contaminated band. The low solubility of plutonium prevents it from leaching quickly and, further, causes it to spread out over a larger area.

Table 6.18 is for a leach rate of 10^{-3} yr^{-1}. The contamination band in this case is about 105 meters for isotopes with a retardation factor of 100. The peak dose rate, about 6000 rem/yr (93% from Am-241) occurs at 20 meters and 1000 years. After 5000 years, americium doses increase with distance away from the borehole (up to 200 m) because the nuclides at the larger distances were released earlier, before the waste was depleted by leaching.

Table 6.19 does not show any increasing annual dose rates with larger distances because the leach rate of 10^{-5} yr^{-1} is so low. The maximum dose rate is 63 rem/yr, 93.1% from Am-241. Cs-135 and Sn-126 dominate all distances until 1000 years when Am-241 reaches the 20-meter distance. Then until 10,000 years Cs-135 and Sn-126 are the prominent nuclides at the large distances while Am-241 and Am-243 dominate up to 200 m.

The smaller leach rates produce lower doses, but the area is contaminated longer. Dose rates from the large leach rates peak high and early, then decrease rapidly. Table 6.20 shows areas contaminated over 0.5 rem/yr. The portion of the table for a leach rate of 10^{-2} yr^{-1} probably underestimates the actual area contaminated, because the very small contamination band may be missed between the points selected for numerical integration.

Granite tank

Tables 6.21 through 6.23 give the annual dose rates resulting from drilling into the water in the granite tank 1000 years after sealing, assuming leach rates of 10^{-2}, 10^{-3}, and 10^{-5} yr^{-1}. Table 5.17 gives the annual dose rates for this event with a leach rate of 10^{-4} yr^{-1}. The dose rates at 20 meters and 1000 years range from 4900 rem/yr at the highest leach rate to 200 rem/yr at the lowest. The amount of a nuclide leached into the tank during the 500 years between canister failure and the 1000-year drilling event is important in controlling the dose rates, particularly at the early dose times and is strongly affected by the leach rate. When the leach rate is 10^{-5} yr^{-1}, only 0.005 of the nuclide has leached into the tank in the 500 years between canister failure and drilling; at 10^{-4} per year, 0.05; at 10^{-3}, 0.39; and, at 10^{-2}, over 0.99. At the lowest leach rate the dose rates increase proportionally to the leach rate (factor of 10 between 10^{-5} and 10^{-4}), but then somewhat higher (factor of about 16 between 10^{-4} and 10^{-3}, and factor of about 25 between 10^{-3} and 10^{-2}). For higher leach rates, the dose rates at later times fall sharply, as the nuclide inventory is depleted. Even at the base case leach rate of 10^{-4} per year, 63% of a nuclide has been removed in 10,000 years.

Table 6.24 shows the areas contaminated at the three leach rates. Less severely contaminated areas (0.5-5 rem/yr) are not greatly affected by leach rate. Very heavily contaminated areas are smaller and less persistent with the lower leach rates. Since the leach rate is not a function of the nuclide itself but of the waste matrix, the same nuclides will dominate the same locations in the aquifers for all leach rates. Cs-135 dominates the first 50 years. At 100 years, Sn-126 has moved to a point where it delivers a dose. Farther downstream is the Cs-135. At 1000 years, Am-241 dominates the dose at 20 meters, followed by Sn-126 and Cs-135. As the Am-241 decays, Am-243 gains in importance. The latter years feature Am-243 and Sn-126 as the important nuclides. As the annual dose rates drop with the decreasing leach rates, the corresponding contaminated areas also decrease.

Brine pocket

This scenario is the same as described in section 5.1.2 with exception of the leach rates examined. Table 6.25 presents the results for a leach rate of 10^{-2} yr^{-1}. The table is very similar to Table 6.17, direct hit with a leach rate of 10^{-2} yr^{-1}. The canisters lose one percent of their inventory every year into a brine pocket around 2 canisters. Due to the very fast leach rate, the Am-241

Table 6.21

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years after Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-2} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.59E-02 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.58E-02 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.53E-02 CS-135 58.8%	9.82E-03 CS-135 58.8%	7.10E-03 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.96E-01 SN-126 92.6%	9.31E-03 CS-135 58.9%	6.75E-03 CS-135 58.9%	5.00E-03 CS-135 58.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.77E-01 SN-126 92.6%	8.37E-03 CS-135 59.2%	6.08E-03 CS-135 59.2%	4.51E-03 CS-135 59.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.31E-01 SN-126 92.7%	9.45E-02 SN-126 93.5%	8.36E-02 SN-126 94.7%	3.29E-03 CS-135 60.0%	2.40E-03 CS-135 60.1%	2.21E-03 CS-135 60.1%	2.15E-03 CS-135 60.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	4.88E+03 AM-241 93.1%	5.70E-02 SN-126 93.6%	5.06E-02 SN-126 94.8%	5.65E-02 SN-126 96.5%	1.42E-03 CS-135 61.4%	1.31E-03 CS-135 61.4%	1.28E-03 CS-135 61.4%	1.32E-03 CS-135 61.5%	1.45E-03 CS-135 61.5%	0.0 NONE 0.0%
2.00E+03	4.81E+02 AM-241 76.6%	2.07E-02 SN-126 93.8%	1.84E-02 SN-126 94.9%	2.06E-02 SN-126 96.6%	5.00E-04 CS-135 64.1%	4.60E-04 CS-135 64.1%	4.49E-04 CS-135 64.1%	4.66E-04 CS-135 64.2%	5.12E-04 CS-135 64.2%	9.37E-04 CS-135 64.2%
5.00E+03	4.45E+00 AM-243 94.8%	1.18E+01 AM-243 95.4%	9.00E+01 AM-243 95.6%	9.93E-04 SN-126 96.8%	2.58E-03 SN-126 99.1%	6.92E-03 SN-126 99.7%	1.96E-02 SN-126 99.9%	2.10E-05 CS-135 70.3%	2.29E-05 CS-135 70.6%	4.20E-05 CS-135 71.3%
1.00E+04	4.00E-02 AM-243 45.2%	6.54E-02 AM-243 73.9%	3.75E-01 AM-243 97.1%	3.05E+01 AM-243 100.0%	1.71E-05 SN-126 98.1%	4.47E-05 SN-126 99.3%	1.26E-04 SN-126 99.8%	1.13E-03 SN-126 100.0%	1.05E-02 SN-126 100.0%	4.92E-07 TC- 99 50.2%

Table 6.22

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-3} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.93E-04 CS-135 57.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	3.96E-04 CS-135 57.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	3.95E-04 CS-135 57.8%	2.50E-04 CS-135 57.8%	1.77E-04 CS-135 57.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	4.83E-03 SN-126 91.8%	2.49E-04 CS-135 58.0%	1.76E-04 CS-135 58.0%	1.25E-04 CS-135 57.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	4.82E-03 SN-126 91.9%	2.47E-04 CS-135 58.3%	1.75E-04 CS-135 58.3%	1.24E-04 CS-135 58.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	4.79E-03 SN-126 92.0%	3.04E-03 SN-126 92.0%	2.15E-03 SN-126 92.0%	1.22E-04 CS-135 59.1%	7.71E-05 CS-135 59.1%	6.30E-05 CS-135 59.1%	5.46E-05 CS-135 59.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.25E+02 AM-241 93.1%	3.00E-03 SN-126 92.1%	2.13E-03 SN-126 92.2%	1.51E-03 SN-126 92.2%	7.48E-05 CS-135 60.6%	6.12E-05 CS-135 60.6%	5.31E-05 CS-135 60.5%	4.35E-05 CS-135 60.5%	3.78E-05 CS-135 60.4%	0.0 NONE 0.0%
2.00E+03	3.31E+01 AM-241 76.5%	2.93E-03 SN-126 92.3%	2.08E-03 SN-126 92.4%	1.48E-03 SN-126 92.4%	7.05E-05 CS-135 63.4%	5.77E-05 CS-135 63.4%	5.01E-05 CS-135 63.3%	4.11E-05 CS-135 63.3%	3.57E-05 CS-135 63.3%	2.55E-05 CS-135 63.1%
5.00E+03	5.96E+00 AM-243 95.0%	3.85E+00 AM-243 95.0%	2.80E+00 AM-243 94.9%	1.38E-03 SN-126 93.0%	8.95E-04 SN-126 93.2%	7.41E-04 SN-126 93.3%	6.48E-04 SN-126 93.3%	3.53E-05 CS-135 70.9%	3.06E-05 CS-135 70.9%	2.20E-05 CS-135 70.9%
1.00E+04	3.45E+00 AM-243 99.0%	2.24E+00 AM-243 99.1%	1.60E+00 AM-243 99.2%	1.20E+00 AM-243 99.2%	8.21E-04 SN-126 93.8%	6.70E-04 SN-126 93.8%	5.85E-04 SN-126 93.8%	4.96E-04 SN-126 94.1%	4.37E-04 SN-126 94.2%	1.83E-05 CS-135 80.8%

Table 6.23

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-5} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	5.55E-04 CS-135 58.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	5.62E-04 CS-135 58.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	5.83E-04 CS-135 58.5%	3.62E-04 CS-135 58.5%	2.48E-04 CS-135 58.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	6.94E-03 SN-126 91.1%	3.83E-04 CS-135 58.6%	2.64E-04 CS-135 58.6%	1.76E-04 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	7.78E-03 SN-126 91.3%	4.21E-04 CS-135 59.0%	2.91E-04 CS-135 58.9%	1.97E-04 CS-135 58.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	9.73E-03 SN-126 91.7%	5.65E-03 SN-126 91.1%	3.24E-03 SN-126 89.1%	2.43E-04 CS-135 59.9%	1.40E-04 CS-135 59.8%	1.04E-04 CS-135 59.8%	7.90E-05 CS-135 59.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.88E+02 AM-241 93.1%	7.15E-03 SN-126 91.8%	4.64E-03 SN-126 91.1%	2.39E-03 SN-126 87.9%	1.75E-04 CS-135 61.3%	1.37E-04 CS-135 61.3%	1.13E-04 CS-135 61.3%	8.06E-05 CS-135 61.2%	5.62E-05 CS-135 61.1%	0.0 NONE 0.0%
2.00E+03	8.50E+01 AM-241 76.6%	8.45E-03 SN-126 92.4%	5.84E-03 SN-126 92.2%	3.84E-03 SN-126 91.7%	2.01E-04 CS-135 64.1%	1.62E-04 CS-135 64.1%	1.39E-04 CS-135 64.1%	1.09E-04 CS-135 64.1%	9.06E-05 CS-135 64.1%	4.01E-05 CS-135 63.9%
5.00E+03	1.66E+01 AM-243 95.5%	1.14E+01 AM-243 95.5%	4.94E+00 AM-243 97.4%	3.86E-03 SN-126 93.7%	2.64E-03 SN-126 94.1%	2.03E-03 SN-126 93.6%	1.21E-03 SN-126 90.6%	9.55E-05 CS-135 71.8%	8.48E-05 CS-135 71.8%	6.43E-05 CS-135 71.8%
1.00E+04	4.39E+00 AM-243 99.9%	3.70E+00 AM-243 99.9%	3.91E+00 AM-243 99.9%	2.51E+00 AM-243 99.8%	1.33E-03 SN-126 95.9%	1.34E-03 SN-126 96.5%	1.39E-03 SN-126 97.0%	1.41E-03 SN-126 97.5%	9.00E-04 SN-126 96.4%	2.77E-05 CS-135 81.9%

Table 6.24

Area (ha*) of the Aquifer Contaminated
Above the Specified Dose Rate Levels
Following Drilling into the Granite Tank
1000 Years after Sealing

Variable leach rate

Leach Rate (per year)	Length of time after event (yr)	Dose Rate Levels (rem/yr) 0.5	5	50	500	5000
10^{-2}	0-50	0	0	0	0	0
	100	0.12	0	0	0	0
	200	0.12	0	0	0	0
	500	0.57	0	0	0	0
	1000	0.51	0.37	0.32	0.25	0.17
	2000	0.38	0.33	0.27	0.19	0.04
	5000	3.00	2.46	1.75	0.38	0
	10000	9.42	7.30	3.98	0	0
10^{-3}	0-50	0	0	0	0	0
	100	0.04	0	0	0	0
	200	0.05	0	0	0	0
	500	0.06	0	0	0	0
	1000	0.40	0.35	0.30	0.23	0.13
	2000	0.37	0.32	0.26	0.18	0
	5000	2.91	2.34	1.58	0	0
	10000	9.15	6.96	3.42	0	0
10^{-5}	0-500	0	0	0	0	0
	1000	0.30	0.24	0.14	0	0
	2000	0.28	0.21	0.09	0	0
	5000	1.83	0.39	0	0	0
	10000	5.15	0	0	0	0

*1 hectare (ha) = 10^4 square meters

Table 6.25

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-2} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	5.46E-05 CS-135 51.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	5.03E-05 CS-135 50.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	3.89E-05 CS-135 48.8%	2.78E-05 CS-135 49.9%	2.41E-05 CS-135 51.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	5.53E-04 SN-126 95.3%	1.84E-05 CS-135 45.7%	1.57E-05 CS-135 47.9%	1.67E-05 CS-135 51.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.07E-04 SN-126 93.5%	9.22E-06 TC -99 43.5%	7.54E-06 TC -99 37.9%	7.38E-06 CS-135 42.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.04E-05 SN-126 92.8%	2.60E-05 SN-126 97.9%	1.95E-04 SN-126 99.8%	5.53E-07 TC -99 52.7%	1.46E-06 TC -99 52.7%	2.90E-06 CS-135 38.4%	6.22E-06 CS-135 51.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	9.72E+00 AM-241 92.6%	1.74E-07 SN-126 97.9%	1.31E-06 SN-126 99.8%	1.08E-04 SN-126 100.0%	9.72E-09 TC -99 53.3%	2.61E-08 TC -99 53.3%	7.44E-08 TC -99 53.3%	6.57E-07 TC -99 53.3%	3.53E-06 CS-135 50.0%	0.0 NONE 0.0%
2.00E+03	1.61E-04 AM-241 55.8%	7.82E-12 SN-126 97.9%	5.88E-11 SN-126 99.8%	4.87E-09 SN-126 100.0%	4.30E-13 TC -99 54.3%	1.16E-12 TC -99 54.3%	3.29E-12 TC -99 54.3%	2.92E-11 TC -99 54.3%	2.73E-10 TC -99 54.3%	1.66E-06 CS-135 46.6%
5.00E+03	5.39E-18 AM-243 36.0%	5.50E-12 AM-243 36.0%	4.97E-02 AM-243 61.7%	4.42E-22 SN-126 100.0%	4.51E-16 SN-126 100.0%	5.46E-11 SN-126 100.0%	6.98E-06 SN-126 100.0%	2.56E-24 TC -99 56.8%	2.39E-23 TC -99 56.8%	2.34E-19 TC -99 56.8%
1.00E+04	6.80E-40 PU-239 39.2%	7.46E-34 PU-239 36.8%	1.14E-23 PU-239 36.8%	3.90E-03 PU-239 36.8%	8.44E-38 SN-126 100.0%	1.01E-32 SN-126 100.0%	1.29E-27 SN-126 100.0%	2.34E-17 SN-126 100.0%	4.41E-07 SN-126 100.0%	4.21E-41 TC -99 59.6%

Table 6.26

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-3} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.59E-02 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.58E-02 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.57E-02 CS-135 58.8%	9.82E-03 CS-135 58.8%	7.10E-03 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.96E-01 SN-126 92.6%	9.31E-03 CS-135 58.9%	6.75E-03 CS-135 58.9%	5.00E-03 CS-135 58.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.77E-01 SN-126 92.6%	8.37E-03 CS-135 59.2%	6.08E-03 CS-135 59.2%	4.51E-03 CS-135 59.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.31E-01 SN-126 92.7%	9.45E-02 SN-126 93.5%	8.36E-02 SN-126 94.7%	3.29E-03 CS-135 60.0%	2.40E-03 CS-135 60.1%	2.21E-03 CS-135 60.1%	2.15E-03 CS-135 60.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	4.88E+03 AM-241 93.1%	5.70E-02 SN-126 93.6%	5.06E-02 SN-126 94.8%	5.65E-02 SN-126 96.5%	1.42E-03 CS-135 61.4%	1.31E-03 CS-135 61.4%	1.28E-03 CS-135 61.4%	1.32E-03 CS-135 61.5%	1.45E-03 CS-135 61.5%	0.0 NONE 0.0%
2.00E+03	4.81E+02 AM-241 76.6%	2.07E-02 SN-126 93.8%	1.84E-02 SN-126 94.9%	2.06E-02 SN-126 96.6%	5.00E-04 CS-135 64.1%	4.60E-04 CS-135 64.1%	4.49E-04 CS-135 64.1%	4.66E-04 CS-135 64.2%	5.12E-04 CS-135 64.2%	9.37E-04 CS-135 64.2%
5.00E+03	4.45E+00 AM-243 94.8%	1.18E+01 AM-243 95.4%	9.00E+01 AM-243 95.6%	9.93E-04 SN-126 96.8%	2.58E-03 SN-126 99.1%	6.92E-03 SN-126 99.7%	1.96E-02 SN-126 99.9%	2.10E-05 CS-135 70.3%	2.29E-05 CS-135 70.6%	4.20E-05 CS-135 71.3%
1.00E+04	4.00E-02 AM-243 45.2%	6.54E-02 AM-243 73.9%	3.75E-01 AM-243 97.1%	3.05E+01 AM-243 100.0%	1.71E-05 SN-126 98.1%	4.47E-05 SN-126 99.3%	1.26E-04 SN-126 99.8%	1.13E-03 SN-126 100.0%	1.05E-02 SN-126 100.0%	4.92E-07 TC -99 50.2%

Table 6.27

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-5} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.93E-04 CS-135 57.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	3.96E-04 CS-135 57.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	3.95E-04 CS-135 57.8%	2.50E-04 CS-135 57.8%	1.77E-04 CS-135 57.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	4.83E-03 SN-126 91.8%	2.49E-04 CS-135 58.0%	1.76E-04 CS-135 58.0%	1.25E-04 CS-135 57.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	4.82E-03 SN-126 91.9%	2.47E-04 CS-135 58.3%	1.75E-04 CS-135 58.3%	1.24E-04 CS-135 58.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	4.79E-03 SN-126 92.0%	3.04E-03 SN-126 92.0%	2.15E-03 SN-126 92.0%	1.22E-04 CS-135 59.1%	7.71E-05 CS-135 59.1%	6.30E-05 CS-135 59.1%	5.46E-05 CS-135 59.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.25E+02 AM-241 93.1%	3.00E-03 SN-126 92.1%	2.13E-03 SN-126 92.2%	1.51E-03 SN-126 92.2%	7.48E-05 CS-135 60.6%	6.12E-05 CS-135 60.6%	5.31E-05 CS-135 60.5%	4.35E-05 CS-135 60.5%	3.78E-05 CS-135 60.4%	0.0 NONE 0.0%
2.00E+03	3.31E+01 AM-241 76.5%	2.93E-03 SN-126 92.3%	2.08E-03 SN-126 92.4%	1.48E-03 SN-126 92.4%	7.05E-05 CS-135 63.4%	5.77E-05 CS-135 63.4%	5.01E-05 CS-135 63.3%	4.11E-05 CS-135 63.3%	3.57E-05 CS-135 63.3%	2.55E-05 CS-135 63.1%
5.00E+03	5.96E+00 AM-243 95.0%	3.85E+00 AM-243 95.0%	2.80E+00 AM-243 94.9%	1.38E-03 SN-126 93.0%	8.95E-04 SN-126 93.2%	7.41E-04 SN-126 93.3%	6.48E-04 SN-126 93.3%	3.53E-05 CS-135 70.9%	3.06E-05 CS-135 70.9%	2.20E-05 CS-135 70.9%
1.00E+04	3.45E+00 AM-243 99.0%	2.24E+00 AM-243 99.1%	1.60E+00 AM-243 99.2%	1.20E+00 AM-243 99.2%	8.21E-04 SN-126 93.8%	6.70E-04 SN-126 93.8%	5.85E-04 SN-126 93.8%	4.96E-04 SN-126 94.1%	4.37E-04 SN-126 94.2%	1.83E-05 CS-135 80.8%

Table 6.28

Area (ha*) of the Aquifer Contaminated Above the Specified Dose Rate Levels Following Drilling into a Brine Pocket 1000 Years after Sealing

Variable leach rates

Leach Rate (per year)	Length of time after event (yr)	Dose limits (rem/yr)			
		0.5	5	50	500
10^{-2}	0-500	0	0	0	0
	1000	0.21	0.10	0	0
	2000-10000		0	0	0
10^{-3}	0-500	0	0	0	0
	1000	0.38	0.33	0.27	0.19
	2000	0.33	0.27	0.19	0
	5000	2.35	1.51	0.56	0
	10000	5.62	3.73	0	0
10^{-5}	0-500	0	0	0	0
	1000	0.29	0.22	0.12	0
	2000	0.25	0.17	0	0
	5000	1.56	0.05	0	0
	10000	3.90	0	0	0

*1 hectare (ha) = 10^4 square meters

is limited by its solubility. In most previous cases the americum never reached its solubility limit. Table 6.26 has the highest dose rate shown on this scenario's tables, 4900 rem/yr for a leach rate of 10^{-3} yr^{-1}. The highest dose rate in Table 6.27 (10^{-5} yr^{-1} leach rate) is 125 rem/yr, while for 10^{-4} yr^{-1} leach rate (Table 5.12) it was 1150 rem/yr. Due to the narrowness of the band of contamination (section 6.3.1), the largest annual dose rate for a 10^{-2} yr^{-1} leach rate is not seen in Table 6.25. The area contaminated by it (Table 6.28) is so small that it is insignificant when averaged over the length of the repository or compared to other areas contaminated.

6.3.2 Release to the aquifer due to faulting

Direct hit on waste

Comparing Tables 6.29, 6.30, 6.31 and 5.22 illustrates the effect of a varying leach rate on doses resulting from a fault line. As the leach rate becomes smaller, the maximum dose rate drops and the time when the maximum dose rate occurs increases.

Reference	L	Maximum Dose Rate (rem/yr)	Time of Maximum (years)
Table 6.29	10^{-2}	4200	100
Table 6.30	10^{-3}	3400	200
Table 5.22	10^{-4}	600	500
Table 6.31	10^{-5}	65	500

Table 6.29 shows no dependence of dose on distance, due to the extremely large leach rate. As soon as the nuclides flow downstream, they are replaced by fresh leachate until the canisters are emptied after several hundred years. Sn-126, Am-241, and Am-243 dominate Table 6.29. Table 6.30 features the same dominant nuclides, with the addition of Pu-239 at 10,000 years, and all the nuclides have been removed from the canisters after several thousand years. There is some

Table 6.29

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Waste Directly Affected
Leach Rate = 10^{-2} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.22E-01 SN-126 58.5%	3.26E-01 SN-126 57.8%	3.26E-01 SN-126 57.8%	3.26E-01 SN-126 57.8%	3.26E-01 SN-126 57.8%	3.26E-01 SN-126 57.8%	3.26E-01 SN-126 57.8%	3.26E-01 SN-126 57.8%	3.26E-01 SN-126 57.8%	3.26E-01 SN-126 57.8%
2.00E+01	5.04E-01 SN-126 76.0%	5.67E-01 SN-126 67.5%	5.67E-01 SN-126 67.5%	5.67E-01 SN-126 67.5%	5.67E-01 SN-126 67.5%	5.67E-01 SN-126 67.5%	5.67E-01 SN-126 67.5%	5.67E-01 SN-126 67.5%	5.67E-01 SN-126 67.5%	5.67E-01 SN-126 67.5%
5.00E+01	5.16E+02 AM-241 98.0%	5.16E+02 AM-241 98.0%	5.16E+02 AM-241 98.0%	5.16E+02 AM-241 98.0%	5.16E+02 AM-241 98.0%	5.16E+02 AM-241 98.0%	5.16E+02 AM-241 98.0%	5.16E+02 AM-241 98.0%	5.16E+02 AM-241 98.0%	5.16E+02 AM-241 98.0%
1.00E+02	4.23E+03 AM-241 97.9%	4.23E+03 AM-241 97.9%	4.23E+03 AM-241 97.9%	4.23E+03 AM-241 97.9%	4.23E+03 AM-241 97.9%	4.23E+03 AM-241 97.9%	4.23E+03 AM-241 97.9%	4.23E+03 AM-241 97.9%	4.23E+03 AM-241 97.9%	4.23E+03 AM-241 97.9%
2.00E+02	2.22E+03 AM-241 97.5%	2.22E+03 AM-241 97.5%	2.22E+03 AM-241 97.5%	2.22E+03 AM-241 97.5%	2.22E+03 AM-241 97.5%	2.22E+03 AM-241 97.5%	2.22E+03 AM-241 97.5%	2.22E+03 AM-241 97.5%	2.22E+03 AM-241 97.5%	2.22E+03 AM-241 97.5%
5.00E+02	8.54E+01 AM-241 92.4%	8.54E+01 AM-241 92.4%	8.54E+01 AM-241 92.4%	8.54E+01 AM-241 92.4%	8.54E+01 AM-241 92.4%	8.54E+01 AM-241 92.4%	8.54E+01 AM-241 92.4%	8.54E+01 AM-241 92.4%	8.54E+01 AM-241 92.4%	8.54E+01 AM-241 92.4%
1.00E+03	2.98E-01 AM-241 84.2%	2.98E-01 AM-241 84.1%	2.98E-01 AM-241 84.1%	2.98E-01 AM-241 84.1%	2.98E-01 AM-241 84.1%	2.98E-01 AM-241 84.1%	2.98E-01 AM-241 84.1%	2.98E-01 AM-241 84.1%	2.98E-01 AM-241 84.1%	2.98E-01 AM-241 84.1%
2.00E+03	4.50E-06 AM-241 55.8%	4.50E-06 AM-241 55.8%	4.50E-06 AM-241 55.7%	4.50E-06 AM-241 55.7%	4.50E-06 AM-241 55.7%	4.50E-06 AM-241 55.7%	4.50E-06 AM-241 55.7%	4.50E-06 AM-241 55.7%	4.50E-06 AM-241 55.7%	4.50E-06 AM-241 55.7%
5.00E+03	1.52E-19 AM-243 35.9%	1.52E-19 AM-243 35.9%	1.52E-19 AM-243 35.9%	1.52E-19 AM-243 35.9%	1.52E-19 AM-243 35.9%	1.52E-19 AM-243 35.9%	1.52E-19 AM-243 35.9%	1.52E-19 AM-243 35.9%	1.52E-19 AM-243 35.9%	1.52E-19 AM-243 35.9%
1.00E+04	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%

Table 6.30

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Waste Directly Affected
Leach Rate = 10^{-3} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.86E-02 SN-126 57.1%	3.91E-02 SN-126 56.4%	3.91E-02 SN-126 56.4%	3.91E-02 SN-126 56.4%	3.91E-02 SN-126 56.4%	3.91E-02 SN-126 56.4%	3.91E-02 SN-126 56.4%	3.91E-02 SN-126 56.4%	3.91E-02 SN-126 56.4%	3.91E-02 SN-126 56.4%
2.00E+01	6.71E-02 SN-126 75.6%	7.66E-02 SN-126 66.3%	7.66E-02 SN-126 66.3%	7.66E-02 SN-126 66.3%	7.66E-02 SN-126 66.3%	7.66E-02 SN-126 66.3%	7.66E-02 SN-126 66.3%	7.66E-02 SN-126 66.3%	7.66E-02 SN-126 66.3%	7.66E-02 SN-126 66.3%
5.00E+01	1.26E+02 AM-241 98.0%	1.26E+02 AM-241 97.9%	1.26E+02 AM-241 97.9%	1.26E+02 AM-241 97.9%	1.26E+02 AM-241 97.9%	1.26E+02 AM-241 97.9%	1.26E+02 AM-241 97.9%	1.26E+02 AM-241 97.9%	1.26E+02 AM-241 97.9%	1.26E+02 AM-241 97.9%
1.00E+02	1.97E+03 AM-241 97.9%	1.97E+03 AM-241 97.9%	1.97E+03 AM-241 97.9%	1.97E+03 AM-241 97.9%	1.97E+03 AM-241 97.9%	1.97E+03 AM-241 97.9%	1.97E+03 AM-241 97.9%	1.97E+03 AM-241 97.9%	1.97E+03 AM-241 97.9%	1.97E+03 AM-241 97.9%
2.00E+02	3.44E+03 AM-241 97.6%	3.45E+03 AM-241 97.6%	3.45E+03 AM-241 97.6%	3.45E+03 AM-241 97.6%	3.45E+03 AM-241 97.6%	3.45E+03 AM-241 97.6%	3.45E+03 AM-241 97.6%	3.45E+03 AM-241 97.6%	3.45E+03 AM-241 97.6%	3.45E+03 AM-241 97.6%
5.00E+02	3.14E+03 AM-241 96.2%	3.14E+03 AM-241 96.2%	3.14E+03 AM-241 96.2%	3.14E+03 AM-241 96.2%	3.14E+03 AM-241 96.2%	3.14E+03 AM-241 96.2%	3.14E+03 AM-241 96.2%	3.14E+03 AM-241 96.2%	3.14E+03 AM-241 96.2%	3.14E+03 AM-241 96.2%
1.00E+03	1.25E+03 AM-241 92.1%	1.27E+03 AM-241 92.1%	1.27E+03 AM-241 92.1%	1.27E+03 AM-241 92.1%	1.27E+03 AM-241 92.1%	1.27E+03 AM-241 92.1%	1.27E+03 AM-241 92.1%	1.27E+03 AM-241 92.1%	1.27E+03 AM-241 92.1%	1.27E+03 AM-241 92.1%
2.00E+03	1.35E+02 AM-241 68.9%	1.68E+02 AM-241 67.5%	1.68E+02 AM-241 67.5%	1.68E+02 AM-241 67.5%	1.68E+02 AM-241 67.4%	1.68E+02 AM-241 67.4%	1.68E+02 AM-241 67.4%	1.68E+02 AM-241 67.4%	1.68E+02 AM-241 67.4%	1.68E+02 AM-241 67.4%
5.00E+03	3.01E+00 AM-243 36.0%	3.71E+00 AM-243 35.9%	3.85E+00 AM-243 35.9%	3.86E+00 AM-243 35.9%	3.86E+00 AM-243 35.9%	3.86E+00 AM-243 35.9%	3.86E+00 AM-243 35.9%	3.86E+00 AM-243 35.9%	3.86E+00 AM-243 35.9%	3.86E+00 AM-243 35.9%
1.00E+04	1.42E-02 PU-239 36.8%	1.75E-02 PU-239 36.8%	1.81E-02 PU-239 36.8%	1.82E-02 PU-239 36.8%	1.82E-02 PU-239 36.7%	1.82E-02 PU-239 36.7%	1.82E-02 PU-239 36.7%	1.82E-02 PU-239 36.7%	1.82E-02 PU-239 36.7%	1.82E-02 PU-239 36.7%

Table 6.31

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Waste Directly Affected
Leach Rate = 10^{-5} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	5.42E-04 SN-126 41.4%	5.52E-04 SN-126 40.6%	5.52E-04 SN-126 40.6%	5.52E-04 SN-126 40.6%	5.52E-04 SN-126 40.6%	5.52E-04 SN-126 40.6%	5.52E-04 SN-126 40.6%	5.52E-04 SN-126 40.6%	5.52E-04 SN-126 40.6%	5.52E-04 SN-126 40.6%
2.00E+01	8.41E-04 SN-126 62.2%	1.03E-03 SN-126 51.0%	1.03E-03 SN-126 51.0%	1.03E-03 SN-126 51.0%	1.03E-03 SN-126 51.0%	1.03E-03 SN-126 51.0%	1.03E-03 SN-126 51.0%	1.03E-03 SN-126 51.0%	1.03E-03 SN-126 51.0%	1.03E-03 SN-126 51.0%
5.00E+01	1.42E+00 AM-241 95.3%	1.42E+00 AM-241 95.3%	1.42E+00 AM-241 95.3%	1.42E+00 AM-241 95.3%	1.42E+00 AM-241 95.3%	1.42E+00 AM-241 95.3%	1.42E+00 AM-241 95.3%	1.42E+00 AM-241 95.3%	1.42E+00 AM-241 95.3%	1.42E+00 AM-241 95.3%
1.00E+02	2.41E+01 AM-241 95.1%	2.41E+01 AM-241 95.1%	2.41E+01 AM-241 95.1%	2.41E+01 AM-241 95.1%	2.41E+01 AM-241 95.1%	2.41E+01 AM-241 95.1%	2.41E+01 AM-241 95.1%	2.41E+01 AM-241 95.1%	2.41E+01 AM-241 95.1%	2.41E+01 AM-241 95.1%
2.00E+02	4.86E+01 AM-241 94.4%	4.86E+01 AM-241 94.4%	4.86E+01 AM-241 94.4%	4.86E+01 AM-241 94.4%	4.86E+01 AM-241 94.4%	4.86E+01 AM-241 94.4%	4.86E+01 AM-241 94.4%	4.86E+01 AM-241 94.4%	4.86E+01 AM-241 94.4%	4.86E+01 AM-241 94.4%
5.00E+02	6.76E+01 AM-241 91.6%	6.76E+01 AM-241 91.6%	6.76E+01 AM-241 91.6%	6.76E+01 AM-241 91.6%	6.76E+01 AM-241 91.6%	6.76E+01 AM-241 91.6%	6.76E+01 AM-241 91.6%	6.76E+01 AM-241 91.6%	6.76E+01 AM-241 91.6%	6.76E+01 AM-241 91.6%
1.00E+03	5.32E+01 AM-241 84.2%	5.48E+01 AM-241 84.2%	5.49E+01 AM-241 84.2%	5.49E+01 AM-241 84.2%	5.49E+01 AM-241 84.2%	5.49E+01 AM-241 84.2%	5.49E+01 AM-241 84.2%	5.49E+01 AM-241 84.2%	5.49E+01 AM-241 84.2%	5.49E+01 AM-241 84.2%
2.00E+03	1.75E+01 AM-241 55.8%	2.75E+01 AM-241 55.8%	2.75E+01 AM-241 55.8%	2.75E+01 AM-241 55.8%	2.75E+01 AM-241 55.8%	2.75E+01 AM-241 55.8%	2.75E+01 AM-241 55.8%	2.75E+01 AM-241 55.8%	2.76E+01 AM-241 55.8%	2.76E+01 AM-241 55.8%
5.00E+03	6.13E+00 AM-243 36.0%	1.07E+01 AM-243 36.0%	1.57E+01 AM-243 36.0%	1.61E+01 AM-243 36.0%	1.61E+01 AM-243 35.9%	1.61E+01 AM-243 35.9%	1.61E+01 AM-243 35.9%	1.61E+01 AM-243 35.9%	1.61E+01 AM-243 35.9%	1.61E+01 AM-243 35.9%
1.00E+04	4.07E+00 PU-239 36.8%	7.09E+00 PU-239 36.8%	1.04E+01 PU-239 36.8%	1.49E+01 PU-239 36.8%	1.53E+01 PU-239 36.8%	1.53E+01 PU-239 36.8%	1.53E+01 PU-239 36.8%	1.53E+01 PU-239 36.8%	1.53E+01 PU-239 36.8%	1.53E+01 PU-239 36.7%

dependence on distance in this case, but not as much as with the low leach rate in Table 6.31. The low leach rate decreases the flow of nuclides from canister to aquifer. The same nuclides dominate the table.

Hit on contaminated repository water

The dominant nuclides and their migration are the same as in the base case for all three leach rate values, but the magnitude of the annual dose rates is different (Tables 6.32, 6.33, 6.34). The maximum dose rate with a leach rate of 10^{-2} yr^{-1} is 6.3×10^{6} rem/yr, 98.0% from Am-241. The maximum for a leach rate of 10^{-3} yr^{-1} is 3.9×10^{6} rem/yr and the maximum for a leach rate of 10^{-5} yr^{-1} is 58,000 rem/yr. The maximum dose rate for a leach rate of 10^{-4} yr^{-1} is 600,000 rem/yr. These doses reflect the entry of nuclides into the granite tank prior to the occurrence of the fault. The flow of water is much larger in this case, leading to rapid depletion of the nuclide inventory. In each case, the highest dose occurs 100 years after the event and along the downstream side of the aquifer (repository). When the leach rate is 10^{-2} yr^{-1}, the nuclides enter the tank quickly and are released along the fault into the aquifer. By 10,000 years there are only low doses over the first two hundred meters of the repository, the Am-243 and other nuclides having flowed downstream. When the leach rate is 10^{-3} yr^{-1}, the waste does not leach as fast, therefore nuclides remain in the waste to feed the tank for a longer time. When the leach rate is 10^{-5} yr^{-1}, the annual dose rates do not become very small in 10,000 years. The concentration is lower and the contamination time is longer. Am-241 and Am-243 are prevalent in all cases, except for Sn-126 very early and Pu-239 at 10,000 years.

6.3.3 Release to the land surface

Tables 6.35 through 6.37 give the annual dose rates resulting from releases to the land surface by drilling into granite repository water having leach rates of 10^{-2}, 10^{-3}, and 10^{-5} yr^{-1}. Table 5.38

Table 6.32

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Repository Water Affected
Leach Rate = 10^{-2} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	7.63E+02 SN-126 54.0%	7.92E+02 SN-126 52.1%	7.92E+02 SN-126 52.1%	7.92E+02 SN-126 52.1%	7.92E+02 SN-126 52.1%	7.92E+02 SN-126 52.1%	7.92E+02 SN-126 52.1%	7.92E+02 SN-126 52.1%	7.92E+02 SN-126 52.1%	7.92E+02 SN-126 52.1%
2.00E+01	4.97E+02 SN-126 89.3%	7.24E+02 SN-126 61.4%	7.24E+02 SN-126 61.4%	7.24E+02 SN-126 61.4%	7.24E+02 SN-126 61.4%	7.24E+02 SN-126 61.4%	7.24E+02 SN-126 61.4%	7.24E+02 SN-126 61.4%	7.24E+02 SN-126 61.4%	7.24E+02 SN-126 61.4%
5.00E+01	3.42E+06 AM-241 95.4%	3.42E+06 AM-241 95.4%	3.42E+06 AM-241 95.4%	3.42E+06 AM-241 95.4%	3.42E+06 AM-241 95.4%	3.42E+06 AM-241 95.4%	3.42E+06 AM-241 95.4%	3.42E+06 AM-241 95.4%	3.42E+06 AM-241 95.4%	3.42E+06 AM-241 95.4%
1.00E+02	6.31E+06 AM-241 95.1%	6.31E+06 AM-241 95.1%	6.31E+06 AM-241 95.1%	6.31E+06 AM-241 95.1%	6.31E+06 AM-241 95.1%	6.31E+06 AM-241 95.1%	6.31E+06 AM-241 95.1%	6.31E+06 AM-241 95.1%	6.31E+06 AM-241 95.1%	6.31E+06 AM-241 95.1%
2.00E+02	3.81E+06 AM-241 94.4%	3.81E+06 AM-241 94.4%	3.81E+06 AM-241 94.4%	3.81E+06 AM-241 94.4%	3.81E+06 AM-241 94.4%	3.81E+06 AM-241 94.4%	3.81E+06 AM-241 94.4%	3.81E+06 AM-241 94.4%	3.81E+06 AM-241 94.4%	3.81E+06 AM-241 94.4%
5.00E+02	1.56E+06 AM-241 91.6%	1.56E+06 AM-241 91.6%	1.56E+06 AM-241 91.6%	1.56E+06 AM-241 91.6%	1.56E+06 AM-241 91.6%	1.56E+06 AM-241 91.6%	1.56E+06 AM-241 91.6%	1.56E+06 AM-241 91.6%	1.56E+06 AM-241 91.6%	1.56E+06 AM-241 91.6%
1.00E+03	1.21E+02 AM-241 84.2%	5.63E+05 AM-241 84.2%	5.63E+05 AM-241 84.2%	5.63E+05 AM-241 84.2%	5.63E+05 AM-241 84.2%	5.63E+05 AM-241 84.2%	5.63E+05 AM-241 84.2%	5.63E+05 AM-241 84.2%	5.63E+05 AM-241 84.2%	5.63E+05 AM-241 84.2%
2.00E+03	7.48E-04 AM-241 55.8%	1.32E+05 AM-241 55.8%	1.32E+05 AM-241 55.8%	1.32E+05 AM-241 55.8%	1.32E+05 AM-241 55.8%	1.32E+05 AM-241 55.8%	1.32E+05 AM-241 55.8%	1.32E+05 AM-241 55.8%	1.32E+05 AM-241 55.8%	1.32E+05 AM-241 55.8%
5.00E+03	2.53E-17 AM-243 36.0%	2.46E-11 AM-243 36.0%	3.76E-01 AM-243 36.0%	3.01E+04 AM-243 36.0%	3.01E+04 AM-243 36.0%	3.01E+04 AM-243 36.0%	3.01E+04 AM-243 36.0%	3.01E+04 AM-243 35.9%	3.01E+04 AM-243 35.9%	3.01E+04 AM-243 35.9%
1.00E+04	0.0 NONE 0.0%	4.92E-34 PU-239 78.5%	5.07E-23 PU-239 36.8%	1.71E-02 PU-239 36.8%	1.49E+04 PU-239 36.8%	1.49E+04 PU-239 36.8%	1.49E+04 PU-239 36.8%	1.49E+04 PU-239 36.8%	1.49E+04 PU-239 36.8%	1.49E+04 PU-239 36.8%

Table 6.33

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Repository Water Affected
Leach Rate = 10^{-3} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	4.55E+02 SN-126 53.9%	4.72E+02 SN-126 52.0%	4.72E+02 SN-126 52.0%	4.72E+02 SN-126 52.0%	4.72E+02 SN-126 52.0%	4.72E+02 SN-126 52.0%	4.72E+02 SN-126 52.0%	4.72E+02 SN-126 52.0%	4.72E+02 SN-126 52.0%	4.72E+02 SN-126 52.0%
2.00E+01	2.99E+02 SN-126 88.9%	4.34E+02 SN-126 61.2%	4.34E+02 SN-126 61.2%	4.34E+02 SN-126 61.2%	4.34E+02 SN-126 61.2%	4.34E+02 SN-126 61.2%	4.34E+02 SN-126 61.2%	4.34E+02 SN-126 61.2%	4.34E+02 SN-126 61.2%	4.34E+02 SN-126 61.2%
5.00E+01	2.03E+06 AM-241 95.4%	2.03E+06 AM-241 95.4%	2.03E+06 AM-241 95.4%	2.03E+06 AM-241 95.4%	2.03E+06 AM-241 95.4%	2.03E+06 AM-241 95.4%	2.03E+06 AM-241 95.4%	2.03E+06 AM-241 95.4%	2.03E+06 AM-241 95.4%	2.03E+06 AM-241 95.4%
1.00E+02	3.89E+06 AM-241 95.1%	3.89E+06 AM-241 95.1%	3.89E+06 AM-241 95.1%	3.89E+06 AM-241 95.1%	3.89E+06 AM-241 95.1%	3.89E+06 AM-241 95.1%	3.89E+06 AM-241 95.1%	3.89E+06 AM-241 95.1%	3.89E+06 AM-241 95.1%	3.89E+06 AM-241 95.1%
2.00E+02	2.54E+06 AM-241 94.4%	2.54E+06 AM-241 94.4%	2.54E+06 AM-241 94.4%	2.54E+06 AM-241 94.4%	2.54E+06 AM-241 94.4%	2.54E+06 AM-241 94.4%	2.54E+06 AM-241 94.4%	2.54E+06 AM-241 94.4%	2.54E+06 AM-241 94.4%	2.54E+06 AM-241 94.4%
5.00E+02	1.27E+06 AM-241 91.6%	1.27E+06 AM-241 91.6%	1.27E+06 AM-241 91.6%	1.27E+06 AM-241 91.6%	1.27E+06 AM-241 91.6%	1.27E+06 AM-241 91.6%	1.27E+06 AM-241 91.6%	1.27E+06 AM-241 91.6%	1.27E+06 AM-241 91.6%	1.27E+06 AM-241 91.6%
1.00E+03	1.99E+05 AM-241 84.2%	5.44E+05 AM-241 84.2%	5.44E+05 AM-241 84.2%	5.44E+05 AM-241 84.2%	5.44E+05 AM-241 84.2%	5.44E+05 AM-241 84.2%	5.44E+05 AM-241 84.2%	5.44E+05 AM-241 84.2%	5.44E+05 AM-241 84.2%	5.44E+05 AM-241 84.21
2.00E+03	2.43E+04 AM-241 55.8%	1.43E+05 AM-241 55.8%	1.43E+05 AM-241 55.8%	1.43E+05 AM-241 55.8%	1.43E+05 AM-241 55.8%	1.43E+05 AM-241 55.8%	1.43E+05 AM-241 55.8%	1.43E+05 AM-241 55.8%	1.43E+05 AM-241 55.8%	1.43E+05 AM-241 55.8%
5.00E+03	4.37E+02 AM-243 36.0%	1.58E+03 AM-243 36.0%	1.15E+04 AM-243 36.0%	3.20E+04 AM-243 36.0%	3.20E+04 AM-243 36.0%	3.20E+04 AM-243 36.0%	3.20E+04 AM-243 36.0%	3.20E+04 AM-243 35.9%	3.20E+04 AM-243 35.9%	3.20E+04 AM-243 35.9%
1.00E+04	2.06E+00 PU-239 36.8%	7.45E+00 PU-239 36.8%	5.42E+01 PU-239 36.8%	4.12E+03 PU-239 36.8%	1.53E+04 PU-239 36.8%	1.53E+04 PU-239 36.8%	1.53E+04 PU-239 36.8%	1.53E+04 PU-239 36.8%	1.53E+04 PU-239 36.8%	1.53E+04 PU-239 36.8%

Table 6.34

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Repository Water Affected
Leach Rate = 10^{-5} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	6.88E+00 SN-126 53.9%	7.14E+00 SN-126 51.9%	7.14E+00 SN-126 51.9%	7.14E+00 SN-126 51.9%	7.14E+00 SN-126 51.9%	7.14E+00 SN-126 51.9%	7.14E+00 SN-126 51.9%	7.14E+00 SN-126 51.9%	7.14E+00 SN-126 51.9%	7.14E+00 SN-126 51.9%
2.00E+01	4.56E+00 SN-126 88.6%	6.60E+00 SN-126 61.2%	6.60E+00 SN-126 61.2%	6.60E+00 SN-126 61.2%	6.60E+00 SN-126 61.2%	6.60E+00 SN-126 61.2%	6.60E+00 SN-126 61.2%	6.60E+00 SN-126 61.2%	6.60E+00 SN-126 61.2%	6.60E+00 SN-126 61.2%
5.00E+01	3.07E+04 AM-241 95.4%	3.07E+04 AM-241 95.4%	3.07E+04 AM-241 95.4%	3.07E+04 AM-241 95.4%	3.07E+04 AM-241 95.4%	3.07E+04 AM-241 95.4%	3.07E+04 AM-241 95.4%	3.07E+04 AM-241 95.4%	3.07E+04 AM-241 95.4%	3.07E+04 AM-241 95.4%
1.00E+02	6.00E+04 AM-241 95.1%	6.00E+04 AM-241 95.1%	6.00E+04 AM-241 95.1%	6.00E+04 AM-241 95.1%	6.00E+04 AM-241 95.1%	6.00E+04 AM-241 95.1%	6.00E+04 AM-241 95.1%	6.00E+04 AM-241 95.1%	6.00E+04 AM-241 95.1%	6.00E+04 AM-241 95.1%
2.00E+02	4.16E+04 AM-241 94.4%	4.16E+04 AM-241 94.4%	4.16E+04 AM-241 94.4%	4.16E+04 AM-241 94.4%	4.16E+04 AM-241 94.4%	4.16E+04 AM-241 94.4%	4.16E+04 AM-241 94.4%	4.16E+04 AM-241 94.4%	4.16E+04 AM-241 94.4%	4.16E+04 AM-241 94.4%
5.00E+02	2.46E+04 AM-241 91.6%	2.46E+04 AM-241 91.6%	2.46E+04 AM-241 91.6%	2.46E+04 AM-241 91.6%	2.46E+04 AM-241 91.6%	2.46E+04 AM-241 91.6%	2.46E+04 AM-241 91.6%	2.46E+04 AM-241 91.6%	2.46E+04 AM-241 91.6%	2.46E+04 AM-241 91.6%
1.00E+03	8.39E+03 AM-241 84.2%	1.37E+04 AM-241 84.2%	1.37E+04 AM-241 84.2%	1.37E+04 AM-241 84.2%	1.37E+04 AM-241 84.2%	1.37E+04 AM-241 84.2%	1.37E+04 AM-241 84.2%	1.37E+04 AM-241 84.2%	1.37E+04 AM-241 84.2%	1.37E+04 AM-241 84.2%
2.00E+03	2.76E+03 AM-241 55.8%	5.55E+03 AM-241 55.8%	5.55E+03 AM-241 55.8%	5.56E+03 AM-241 55.8%	5.56E+03 AM-241 55.8%	5.56E+03 AM-241 55.8%	5.56E+03 AM-241 55.8%	5.56E+03 AM-241 55.8%	5.56E+03 AM-241 55.8%	5.56E+03 AM-241 55.8%
5.00E+03	9.67E+02 AM-243 36.0%	1.70E+03 AM-243 36.0%	2.54E+03 AM-243 36.0%	2.87E+03 AM-243 36.0%	2.87E+03 AM-243 35.9%	2.87E+03 AM-243 35.9%	2.87E+03 AM-243 35.9%	2.87E+03 AM-243 35.9%	2.87E+03 AM-243 35.9%	2.87E+03 AM-243 35.9%
1.00E+04	6.43E+02 PU-239 36.8%	1.13E+03 PU-239 36.8%	1.69E+03 PU-239 36.8%	2.50E+03 PU-239 36.8%	2.68E+03 PU-239 36.8%	2.68E+03 PU-239 36.8%	2.68E+03 PU-239 36.8%	2.68E+03 PU-239 36.8%	2.68E+03 PU-239 36.8%	2.68E+03 PU-239 36.7%

Table 6.35

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-2} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.47E+01 AM-241 98.2%	3.88E+00 AM-241 98.2%	1.40E+00 AM-241 98.2%	5.03E-01 AM-241 98.2%	1.26E-01 AM-241 98.2%	6.71E-02 AM-241 98.2%	4.26E-02 AM-241 98.2%	2.22E-02 AM-241 98.2%	1.38E-02 AM-241 98.2%	4.22E-03 AM-241 98.2%
2.00E+01	1.44E+01 AM-241 98.2%	3.80E+00 AM-241 98.2%	1.38E+00 AM-241 98.2%	4.93E-01 AM-241 98.2%	1.23E-01 AM-241 98.2%	6.58E-02 AM-241 98.2%	4.18E-02 AM-241 98.2%	2.18E-02 AM-241 98.2%	1.36E-02 AM-241 98.2%	4.13E-03 AM-241 98.2%
5.00E+01	1.35E+01 AM-241 98.1%	3.58E+00 AM-241 98.1%	1.30E+00 AM-241 98.1%	4.64E-01 AM-241 98.1%	1.16E-01 AM-241 98.1%	6.19E-02 AM-241 98.1%	3.94E-02 AM-241 98.1%	2.05E-02 AM-241 98.1%	1.28E-02 AM-241 98.1%	3.89E-03 AM-241 98.1%
1.00E+02	1.22E+01 AM-241 98.0%	3.24E+00 AM-241 98.0%	1.17E+00 AM-241 98.0%	4.20E-01 AM-241 98.0%	1.05E-01 AM-241 98.0%	5.60E-02 AM-241 98.0%	3.56E-02 AM-241 98.0%	1.86E-02 AM-241 98.0%	1.16E-02 AM-241 98.0%	3.52E-03 AM-241 98.0%
2.00E+02	1.00E+01 AM-241 97.7%	2.65E+00 AM-241 97.7%	9.61E-01 AM-241 97.7%	3.44E-01 AM-241 97.7%	8.61E-02 AM-241 97.7%	4.59E-02 AM-241 97.7%	2.92E-02 AM-241 97.7%	1.52E-02 AM-241 97.7%	9.48E-03 AM-241 97.7%	2.89E-03 AM-241 97.7%
5.00E+02	5.54E+00 AM-241 96.6%	1.47E+00 AM-241 96.6%	5.31E-01 AM-241 96.6%	1.90E-01 AM-241 96.6%	4.75E-02 AM-241 96.6%	2.54E-02 AM-241 96.6%	1.61E-02 AM-241 96.6%	8.40E-03 AM-241 96.6%	5.24E-03 AM-241 96.6%	1.59E-03 AM-241 96.6%
1.00E+03	2.09E+00 AM-241 93.3%	5.53E-01 AM-241 93.3%	2.00E-01 AM-241 93.3%	7.17E-02 AM-241 93.3%	1.79E-02 AM-241 93.3%	9.57E-03 AM-241 93.3%	6.08E-03 AM-241 93.3%	3.17E-03 AM-241 93.3%	1.98E-03 AM-241 93.3%	6.01E-04 AM-241 93.3%
2.00E+03	3.36E-01 AM-241 77.2%	8.89E-02 AM-241 77.2%	3.22E-02 AM-241 77.2%	1.15E-02 AM-241 77.2%	2.88E-03 AM-241 77.2%	1.54E-03 AM-241 77.2%	9.78E-04 AM-241 77.2%	5.10E-04 AM-241 77.2%	3.18E-04 AM-241 77.2%	9.67E-05 AM-241 77.2%
5.00E+03	1.35E-02 AM-243 95.4%	3.56E-03 AM-243 95.4%	1.29E-03 AM-243 95.4%	4.62E-04 AM-243 95.4%	1.15E-04 AM-243 95.4%	6.16E-05 AM-243 95.4%	3.92E-05 AM-243 95.4%	2.04E-05 AM-243 95.4%	1.27E-05 AM-243 95.4%	3.87E-06 AM-243 95.4%
1.00E+04	6.54E-04 AM-243 100.0%	1.73E-04 AM-243 100.0%	6.27E-05 AM-243 100.0%	2.24E-05 AM-243 100.0%	5.61E-06 AM-243 100.0%	2.99E-06 AM-243 100.0%	1.90E-06 AM-243 100.0%	9.92E-07 AM-243 100.0%	6.18E-07 AM-243 100.0%	1.88E-07 AM-243 100.0%

Table 6.36

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-3} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	5.81E+00 AM-241 98.2%	1.54E+00 AM-241 98.2%	5.56E-01 AM-241 98.2%	1.99E-01 AM-241 98.2%	4.98E-02 AM-241 98.2%	2.66E-02 AM-241 98.2%	1.69E-02 AM-241 98.2%	8.81E-03 AM-241 98.2%	5.49E-03 AM-241 98.2%	1.67E-03 AM-241 98.2%
2.00E+01	5.69E+00 AM-241 98.2%	1.50E+00 AM-241 98.2%	5.45E-01 AM-241 98.2%	1.95E-01 AM-241 98.2%	4.88E-02 AM-241 98.2%	2.60E-02 AM-241 98.2%	1.66E-02 AM-241 98.2%	8.63E-03 AM-241 98.2%	5.38E-03 AM-241 98.2%	1.64E-03 AM-241 98.2%
5.00E+01	5.36E+00 AM-241 98.1%	1.42E+00 AM-241 98.1%	5.13E-01 AM-241 98.1%	1.84E-01 AM-241 98.1%	4.60E-02 AM-241 98.1%	2.45E-02 AM-241 98.1%	1.56E-02 AM-241 98.1%	8.13E-03 AM-241 98.1%	5.06E-03 AM-241 98.1%	1.54E-03 AM-241 98.1%
1.00E+02	4.85E+00 AM-241 98.0%	1.28E+00 AM-241 98.0%	4.65E-01 AM-241 98.0%	1.66E-01 AM-241 98.0%	4.16E-02 AM-241 98.0%	2.22E-02 AM-241 98.0%	1.41E-02 AM-241 98.0%	7.36E-03 AM-241 98.0%	4.58E-03 AM-241 98.0%	1.40E-03 AM-241 98.0%
2.00E+02	3.98E+00 AM-241 97.7%	1.05E+00 AM-241 97.7%	3.81E-01 AM-241 97.7%	1.36E-01 AM-241 97.7%	3.41E-02 AM-241 97.7%	1.82E-02 AM-241 97.7%	1.16E-02 AM-241 97.7%	6.03E-03 AM-241 97.7%	3.76E-03 AM-241 97.7%	1.14E-03 AM-241 97.7%
5.00E+02	2.20E+00 AM-241 96.6%	5.80E-01 AM-241 96.6%	2.10E-01 AM-241 96.6%	7.53E-02 AM-241 96.6%	1.88E-02 AM-241 96.6%	1.00E-02 AM-241 96.6%	6.39E-03 AM-241 96.6%	3.33E-03 AM-241 96.6%	2.07E-03 AM-241 96.6%	6.31E-04 AM-241 96.6%
1.00E+03	8.29E-01 AM-241 93.3%	2.19E-01 AM-241 93.3%	7.93E-02 AM-241 93.3%	2.84E-02 AM-241 93.3%	7.10E-03 AM-241 93.3%	3.79E-03 AM-241 93.3%	2.41E-03 AM-241 93.3%	1.26E-03 AM-241 93.3%	7.83E-04 AM-241 93.3%	2.38E-04 AM-241 93.3%
2.00E+03	1.33E-01 AM-241 77.2%	3.52E-02 AM-241 77.2%	1.28E-02 AM-241 77.2%	4.57E-03 AM-241 77.2%	1.14E-03 AM-241 77.2%	6.09E-04 AM-241 77.2%	3.87E-04 AM-241 77.2%	2.02E-04 AM-241 77.2%	1.26E-04 AM-241 77.2%	3.83E-05 AM-241 77.2%
5.00E+03	5.34E-03 AM-243 95.4%	1.41E-03 AM-243 95.4%	5.11E-04 AM-243 95.4%	1.83E-04 AM-243 95.4%	4.58E-05 AM-243 95.4%	2.44E-05 AM-243 95.4%	1.55E-05 AM-243 95.4%	8.09E-06 AM-243 95.4%	5.04E-06 AM-243 95.4%	1.53E-06 AM-243 95.4%
1.00E+04	2.59E-04 AM-243 99.9%	6.86E-05 AM-243 99.9%	2.48E-05 AM-243 99.9%	8.89E-06 AM-243 99.9%	2.22E-06 AM-243 99.9%	1.19E-06 AM-243 99.9%	7.54E-07 AM-243 99.9%	3.93E-07 AM-243 99.9%	2.45E-07 AM-243 99.9%	7.46E-08 AM-243 99.9%

Table 6.37

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-5} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	7.37E-02 AM-241 98.1%	1.95E-02 AM-241 98.1%	7.06E-03 AM-241 98.1%	2.53E-03 AM-241 98.1%	6.32E-04 AM-241 98.1%	3.37E-04 AM-241 98.1%	2.14E-04 AM-241 98.1%	1.12E-04 AM-241 98.1%	6.96E-05 AM-241 98.1%	2.12E-05 AM-241 98.1%
2.00E+01	7.23E-02 AM-241 98.0%	1.91E-02 AM-241 98.0%	6.92E-03 AM-241 98.0%	2.48E-03 AM-241 98.0%	6.19E-04 AM-241 98.0%	3.31E-04 AM-241 98.1%	2.10E-04 AM-241 98.0%	1.10E-04 AM-241 98.0%	6.82E-05 AM-241 98.0%	2.08E-05 AM-241 98.0%
5.00E+01	6.81E-02 AM-241 98.0%	1.80E-02 AM-241 98.0%	6.52E-03 AM-241 98.0%	2.33E-03 AM-241 98.0%	5.83E-04 AM-241 98.0%	3.11E-04 AM-241 98.0%	1.98E-04 AM-241 98.0%	1.03E-04 AM-241 98.0%	6.43E-05 AM-241 98.0%	1.96E-05 AM-241 98.0%
1.00E+02	6.16E-02 AM-241 97.9%	1.63E-02 AM-241 97.9%	5.90E-03 AM-241 97.9%	2.11E-03 AM-241 97.9%	5.28E-04 AM-241 97.9%	2.82E-04 AM-241 97.9%	1.79E-04 AM-241 97.9%	9.34E-05 AM-241 97.9%	5.82E-05 AM-241 97.9%	1.77E-05 AM-241 97.9%
2.00E+02	5.05E-02 AM-241 97.6%	1.33E-02 AM-241 97.6%	4.83E-03 AM-241 97.6%	1.73E-03 AM-241 97.6%	4.33E-04 AM-241 97.6%	2.31E-04 AM-241 97.6%	1.47E-04 AM-241 97.6%	7.65E-05 AM-241 97.6%	4.77E-05 AM-241 97.6%	1.45E-05 AM-241 97.6%
5.00E+02	2.79E-02 AM-241 96.4%	7.37E-03 AM-241 96.4%	2.67E-03 AM-241 96.4%	9.56E-04 AM-241 96.4%	2.39E-04 AM-241 96.4%	1.28E-04 AM-241 96.4%	8.11E-05 AM-241 96.4%	4.23E-05 AM-241 96.4%	2.64E-05 AM-241 96.4%	8.02E-06 AM-241 96.4%
1.00E+03	1.06E-02 AM-241 92.9%	2.79E-03 AM-241 92.9%	1.01E-03 AM-241 92.9%	3.62E-04 AM-241 92.9%	9.05E-05 AM-241 92.9%	4.83E-05 AM-241 92.9%	3.07E-05 AM-241 92.9%	1.60E-05 AM-241 92.9%	9.97E-06 AM-241 92.9%	3.03E-06 AM-241 92.9%
2.00E+03	1.72E-03 AM-241 75.9%	4.54E-04 AM-241 75.9%	1.64E-04 AM-241 75.9%	5.88E-05 AM-241 75.9%	1.47E-05 AM-241 75.9%	7.85E-06 AM-241 75.9%	4.99E-06 AM-241 75.9%	2.60E-06 AM-241 75.9%	1.62E-06 AM-241 75.9%	4.93E-07 AM-241 75.9%
5.00E+03	7.24E-05 AM-243 89.1%	1.91E-05 AM-243 89.1%	6.93E-06 AM-243 89.1%	2.48E-06 AM-243 89.1%	6.21E-07 AM-243 89.1%	3.31E-07 AM-243 89.1%	2.11E-07 AM-243 89.1%	1.10E-07 AM-243 89.1%	6.84E-08 AM-243 89.1%	2.08E-08 AM-243 89.1%
1.00E+04	3.55E-06 AM-243 92.6%	9.37E-07 AM-243 92.6%	3.40E-07 AM-243 92.6%	1.22E-07 AM-243 92.6%	3.04E-08 AM-243 92.6%	1.62E-08 AM-243 92.6%	1.03E-08 AM-243 92.6%	5.38E-09 AM-243 92.6%	3.35E-09 AM-243 92.6%	1.02E-09 AM-243 92.6%

gives the annual dose rates for a leach rate of 10^{-4} yr^{-1}. Tables 6.38 through 6.40 give the comparable dose rates from drilling into a brine pocket. Table 5.34 is the comparable table for a leach rate of 10^{-4} yr^{-1}.

In both granite and salt, the annual dose rates are higher for higher leach rates. In granite, the maximum dose rates go from 15 rem/yr for 10^{-2} yr^{-1} leaching to 0.07 rem/yr for 10^{-5} yr^{-1} leaching; in salt, they go from 0.4 to 0.02 rem/yr for the same leach rate range.

6.4 Effect of Varying the Retardation Factors

The annual dose rate from a nuclide depends on the retardation factor "k" primarily through the "U" term (equations 4.41, 4.42, 4.43, and 4.45) which imposes the obvious requirement that there is no dose from a nuclide at places the nuclide has not reached. We might consider that nuclides moving very slowly because of a high retardation factor would be concentrated because the same amount of nuclide would reach the aquifer and be confined to a smaller volume. However, in the real situation, the high retardation factor occurs because the nuclide is largely adsorbed on rock and not available to the water, so that the nuclide concentration in water that it reaches is affected only secondarily.

In the following sections, we consider, separately, release scenarios using retardation factors of one and higher-than-base-case retardation factors.

When the retardation factor is one, all nuclides move with the speed of the groundwater, i.e., 2.1 m/yr. Accordingly, all nuclides reach the first dose distance of 20 meters in ten years so that early annual dose rates are much higher than they are in the base case where the most important nuclide, Am-241, takes 950 years to travel 20 meters.

Table 6.38

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-2} per year

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	4.11E-01 AM-241 63.7%	1.09E-01 AM-241 63.7%	3.94E-02 AM-241 63.7%	1.41E-02 AM-241 63.7%	3.53E-03 AM-241 63.7%	1.88E-03 AM-241 63.7%	1.20E-03 AM-241 63.7%	6.24E-04 AM-241 63.7%	3.88E-04 AM-241 63.7%	1.18E-04 AM-241 63.7%
2.00E+01	3.95E-01 AM-241 64.9%	1.05E-01 AM-241 64.9%	3.79E-02 AM-241 64.9%	1.36E-02 AM-241 64.9%	3.39E-03 AM-241 64.9%	1.81E-03 AM-241 64.9%	1.15E-03 AM-241 64.9%	5.99E-04 AM-241 64.9%	3.73E-04 AM-241 64.9%	1.14E-04 AM-241 64.9%
5.00E+01	3.53E-01 AM-241 68.4%	9.33E-02 AM-241 68.4%	3.38E-02 AM-241 68.4%	1.21E-02 AM-241 68.4%	3.03E-03 AM-241 68.4%	1.62E-03 AM-241 68.4%	1.03E-03 AM-241 68.4%	5.35E-04 AM-241 68.4%	3.33E-04 AM-241 68.4%	1.01E-04 AM-241 68.4%
1.00E+02	2.97E-01 AM-241 73.6%	7.85E-02 AM-241 73.6%	2.84E-02 AM-241 73.6%	1.02E-02 AM-241 73.6%	2.55E-03 AM-241 73.6%	1.36E-03 AM-241 73.6%	8.63E-04 AM-241 73.6%	4.50E-04 AM-241 73.6%	2.80E-04 AM-241 73.6%	8.54E-05 AM-241 73.6%
2.00E+02	2.20E-01 AM-241 81.0%	5.83E-02 AM-241 81.0%	2.11E-02 AM-241 81.0%	7.56E-03 AM-241 81.0%	1.89E-03 AM-241 81.0%	1.01E-03 AM-241 81.0%	6.41E-04 AM-241 81.0%	3.34E-04 AM-241 81.0%	2.08E-04 AM-241 81.0%	6.34E-05 AM-241 81.0%
5.00E+02	1.12E-01 AM-241 87.2%	2.95E-02 AM-241 87.2%	1.07E-02 AM-241 87.2%	3.83E-03 AM-241 87.2%	9.58E-04 AM-241 87.2%	5.11E-04 AM-241 87.2%	3.25E-04 AM-241 87.2%	1.69E-04 AM-241 87.2%	1.06E-04 AM-241 87.2%	3.21E-05 AM-241 87.2%
1.00E+03	4.45E-02 AM-241 79.9%	1.18E-02 AM-241 79.9%	4.26E-03 AM-241 79.9%	1.52E-03 AM-241 79.9%	3.81E-04 AM-241 79.9%	2.04E-04 AM-241 79.9%	1.29E-04 AM-241 79.9%	6.74E-05 AM-241 79.9%	4.20E-05 AM-241 79.9%	1.28E-05 AM-241 79.9%
2.00E+03	9.64E-03 AM-243 51.0%	2.55E-03 AM-243 51.0%	9.23E-04 AM-243 51.0%	3.30E-04 AM-243 51.0%	8.26E-05 AM-243 51.0%	4.41E-05 AM-243 51.0%	2.80E-05 AM-243 51.0%	1.46E-05 AM-243 51.0%	9.10E-06 AM-243 51.0%	2.77E-06 AM-243 51.0%
5.00E+03	8.35E-04 AM-243 98.7%	2.21E-04 AM-243 98.7%	7.99E-05 AM-243 98.7%	2.86E-05 AM-243 98.7%	7.16E-06 AM-243 98.7%	3.82E-06 AM-243 98.7%	2.43E-06 AM-243 98.7%	1.27E-06 AM-243 98.7%	7.88E-07 AM-243 98.7%	2.40E-07 AM-243 98.7%
1.00E+04	4.19E-05 AM-243 100.0%	1.11E-05 AM-243 100.0%	4.01E-06 AM-243 100.0%	1.44E-06 AM-243 100.0%	3.59E-07 AM-243 100.0%	1.92E-07 AM-243 100.0%	1.22E-07 AM-243 100.0%	6.36E-08 AM-243 100.0%	3.96E-08 AM-243 100.0%	1.21E-08 AM-243 100.0%

Table 6.39

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
Leach Rate = 10^{-3} per year

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.57E-01 AM-241 73.3%	9.44E-02 AM-241 73.3%	3.42E-02 AM-241 73.3%	1.22E-02 AM-241 73.3%	3.06E-03 AM-241 73.3%	1.63E-03 AM-241 73.3%	1.04E-03 AM-241 73.3%	5.41E-04 AM-241 73.3%	3.37E-04 AM-241 73.3%	1.03E-04 AM-241 73.3%
2.00E+01	3.46E-01 AM-241 74.3%	9.13E-02 AM-241 74.3%	3.31E-02 AM-241 74.3%	1.18E-02 AM-241 74.3%	2.96E-03 AM-241 74.3%	1.58E-03 AM-241 74.3%	1.00E-03 AM-241 74.3%	5.24E-04 AM-241 74.3%	3.26E-04 AM-241 74.3%	9.93E-05 AM-241 74.3%
5.00E+01	3.14E-01 AM-241 76.9%	8.30E-02 AM-241 76.9%	3.01E-02 AM-241 76.9%	1.08E-02 AM-241 76.9%	2.69E-03 AM-241 76.9%	1.44E-03 AM-241 76.9%	9.14E-04 AM-241 76.9%	4.76E-04 AM-241 76.9%	2.97E-04 AM-241 76.9%	9.03E-05 AM-241 76.9%
1.00E+02	2.71E-01 AM-241 80.5%	7.17E-02 AM-241 80.5%	2.60E-02 AM-241 80.5%	9.30E-03 AM-241 80.5%	2.33E-03 AM-241 80.5%	1.24E-03 AM-241 80.5%	7.89E-04 AM-241 80.5%	4.11E-04 AM-241 80.5%	2.56E-04 AM-241 80.5%	7.80E-05 AM-241 80.5%
2.00E+02	2.09E-01 AM-241 85.3%	5.53E-02 AM-241 85.3%	2.00E-02 AM-241 85.3%	7.17E-03 AM-241 85.3%	1.79E-03 AM-241 85.3%	9.57E-04 AM-241 85.3%	6.09E-04 AM-241 85.3%	3.17E-04 AM-241 85.3%	1.98E-04 AM-241 85.3%	6.02E-05 AM-241 85.3%
5.00E+02	1.11E-01 AM-241 87.9%	2.93E-02 AM-241 87.9%	1.06E-02 AM-241 87.9%	3.80E-03 AM-241 87.9%	9.50E-04 AM-241 87.9%	5.07E-04 AM-241 87.9%	3.22E-04 AM-241 87.9%	1.68E-04 AM-241 87.9%	1.05E-04 AM-241 87.9%	3.19E-05 AM-241 87.9%
1.00E+03	4.45E-02 AM-241 79.9%	1.18E-02 AM-241 79.9%	4.26E-03 AM-241 79.9%	1.52E-03 AM-241 79.9%	3.81E-04 AM-241 79.9%	2.03E-04 AM-241 79.9%	1.29E-04 AM-241 79.9%	6.74E-05 AM-241 79.9%	4.20E-05 AM-241 79.9%	1.28E-05 AM-241 79.9%
2.00E+03	9.64E-03 AM-243 51.0%	2.55E-03 AM-243 51.0%	9.23E-04 AM-243 51.0%	3.30E-04 AM-243 51.0%	8.26E-05 AM-243 51.0%	4.41E-05 AM-243 51.0%	2.80E-05 AM-243 51.0%	1.46E-05 AM-243 51.0%	9.10E-06 AM-243 51.0%	2.77E-06 AM-243 51.0%
5.00E+03	8.35E-04 AM-243 98.7%	2.21E-04 AM-243 98.7%	7.99E-05 AM-243 98.7%	2.86E-05 AM-243 98.7%	7.16E-06 AM-243 98.7%	3.82E-06 AM-243 98.7%	2.43E-06 AM-243 98.7%	1.27E-06 AM-243 98.7%	7.88E-07 AM-243 98.7%	2.40E-07 AM-243 98.7%
1.00E+04	4.19E-05 AM-243 100.0%	1.11E-05 AM-243 100.0%	4.01E-06 AM-243 100.0%	1.44E-06 AM-243 100.0%	3.59E-07 AM-243 100.0%	1.92E-07 AM-243 100.0%	1.22E-07 AM-243 100.0%	6.36E-08 AM-243 100.0%	3.96E-08 AM-243 100.0%	1.21E-08 AM-243 100.0%

Table 6.40

Dose Equivalent Rates (rem/yr) from Breathing Air Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years after Repository Sealing

Drill Hits Repository Water
Leach rate = 10^{-5} per year

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.14E-02 AM-241 73.3%	5.66E-03 AM-241 73.3%	2.05E-03 AM-241 73.3%	7.35E-04 AM-241 73.3%	1.84E-04 AM-241 73.3%	9.80E-05 AM-241 73.3%	6.23E-05 AM-241 73.3%	3.25E-05 AM-241 73.3%	2.02E-05 AM-241 73.3%	6.16E-06 AM-241 73.3%
2.00E+01	2.07E-02 AM-241 74.3%	5.48E-03 AM-241 74.3%	1.98E-03 AM-241 74.3%	7.11E-04 AM-241 74.3%	1.78E-04 AM-241 74.3%	9.49E-05 AM-241 74.3%	6.03E-05 AM-241 74.3%	3.14E-05 AM-241 74.3%	1.96E-05 AM-241 74.3%	5.96E-06 AM-241 74.3%
5.00E+01	1.88E-02 AM-241 76.9%	4.98E-03 AM-241 76.9%	1.80E-03 AM-241 76.9%	6.46E-04 AM-241 76.9%	1.62E-04 AM-241 76.9%	8.62E-05 AM-241 76.9%	5.48E-05 AM-241 76.9%	2.86E-05 AM-241 76.9%	1.78E-05 AM-241 76.9%	5.42E-06 AM-241 76.9%
1.00E+02	1.63E-02 AM-241 80.5%	4.30E-03 AM-241 80.5%	1.56E-03 AM-241 80.5%	5.58E-04 AM-241 80.5%	1.40E-04 AM-241 80.5%	7.44E-05 AM-241 80.5%	4.73E-05 AM-241 80.5%	2.47E-05 AM-241 80-.5%	1.54E-05 AM-241 80.5%	4.68E-06 AM-241 80.5%
2.00E+02	1.26E-02 AM-241 85.3%	3.32E-03 AM-241 85.3%	1.20E-03 AM-241 85.3%	4.30E-04 AM-241 85.3%	1.08E-04 AM-241 85.3%	5.74E-05 AM-241 85.3%	3.65E-05 AM-241 85.3%	1.90E-05 AM-241 85.3%	1.19E-05 AM-241 85.3%	3.61E-06 AM-241 85.3%
5.00E+02	6.65E-03 AM-241 87.9%	1.76E-03 AM-241 87.9%	6.37E-04 AM-241 87.9%	2.28E-04 AM-241 87.9%	5.70E-05 AM-241 87.9%	3.04E-05 AM-241 87.9%	1.93E-05 AM-241 87.9%	1.01E-05 AM-241 87.9%	6.28E-06 AM-241 87.9%	1.91E-06 AM-241 87.9%
1.00E+03	2.67E-03 AM-241 79.9%	7.05E-04 AM-241 79.9%	2.55E-04 AM-241 79.9%	9.15E-05 AM-241 79.9%	2.29E-05 AM-241 79.9%	1.22E-05 AM-241 79.9%	7.76E-06 AM-241 79.9%	4.04E-06 AM-241 79.9%	2.52E-06 AM-241 79.9%	7.67E-07 AM-241 79.9%
2.00E+03	5.78E-04 AM-243 51.0%	1.53E-04 AM-243 51.0%	5.54E-05 AM-243 51.0%	1.98E-05 AM-243 51.0%	4.96E-06 AM-243 51.0%	2.65E-06 AM-243 51.0%	1.68E-06 AM-243 51.0%	8.77E-07 AM-243 51.0%	5.46E-07 AM-243 51.0%	1.66E-07 AM-243 51.0%
5.00E+03	5.01E-05 AM-243 98.7%	1.32E-05 AM-243 98.7%	4.80E-06 AM-243 98.7%	1.72E-06 AM-243 98.7%	4.29E-07 AM-243 98.7%	2.29E-07 AM-243 98.7%	1.46E-07 AM-243 98.7%	7.59E-08 AM-243 98.7%	4.73E-08 AM-243 98.7%	1.44E-08 AM-243 98.7%
1.00E+04	2.52E-06 AM-243 100.0%	6.65E-07 AM-243 100.0%	2.41E-07 AM-243 100.0%	8.62E-08 AM-243 100.0%	2.16E-08 AM-243 100.0%	1.15E-08 AM-243 100.0%	7.32E-09 AM-243 100.0%	3.81E-09 AM-243 100.0%	2.38E-09 AM-243 100.0%	7.23E-10 AM-243 100.0%

6.4.1 All retardation factors equal one

Release to the aquifer due to drilling: Direct hit on waste

Tables 6.41 and 6.47 give the annual dose rates and contaminated areas, respectively, for a direct hit, drilling release to the aquifer because of drilling into the granite repository when the retardation factors are all equal to one. The annual dose rates can be compared to those in Table 5.7. The annual dose rates, until 500 years, are a factor of about 1,000,000 times larger than those of the base case, primarily because Am-241 moves 20 meters in only 10 years rather than 1000. The peak dose rate of 2660 rem/yr, 98.2% from Am-241, occurs at 10 years, 20 meters. The nuclides and their accompanying high dose rates quickly spread through the aquifer. Later, dose rates near the borehole (e.g., 20 meters at 1000 years) are slightly lower than those of the base case (e.g., 570 rem/yr instead of 630 rem/yr at 1000 years and 20 meters) because the nuclides have flowed beyond the distance considered. In the expression describing the release (equation 4.4) we have the term "$\exp(\lambda_L kx/v)$", k is now much smaller, so this term has a visible, although smaller, influence on the results.

The effect of low retardation factors is best seen by comparing Table 6.47 with Table 5.11. Table 6.47 shows that much larger areas are contaminated very badly at early times, and also that the spread of contamination at later times is greater by two to three orders of magnitude. The contaminated areas over 0.5 rem/yr increase steadily until 2000 years, when the entire length of aquifer studied has been contaminated. After 2000 years, radiological decay and flow of the nuclides cause the area of contamination to drop.

Release to the aquifer due to drilling: Granite tank

Table 6.44 gives the annual dose rates for a release to the aquifer because of drilling into the granite tank when all the retardation factors equal one. The highest dose rate, 14,000 rem/yr, occurs at the earliest time and closest point, ten years and 20 meters, because all nuclides reach this distance within ten years. Am-241 is the maximum contributor until about 2000 years, then Am-243 becomes dominant. The dose rate decreases steadily with both time and distance. Table 6.47 shows that the contaminated areas reach a maximum of 360 ha 2000 years after the event. The areas increase rapidly as the nuclides spread, reach a maximum value, then shrink as the nuclides decay. This is the only drilling event that has any contaminated areas that would give more than 5000 rem/yr for the first 500 years after the event.

Release to the aquifer due to drilling: Brine pocket

Table 6.43 gives the annual dose rates from drinking aquifer water after drilling into a brine pocket 1000 years after the repository was sealed and all retardation factors equal to one. The annual dose rates in Table 6.43 are slightly less than twice those of Table 6.41, reflecting the fact that the brine pocket is in contact with waste from two canisters. The maximum dose rate is 4800 rem/yr, almost all from Am-241, 10 years after the event at a distance of 20 meters. Am-241 dominates until after 2000 years, then decays and Am-243 dominates to 10,000 years.

Table 6.47 shows the areas contaminated above specific dose rate levels. The contamination spreads very quickly. The discussion in the direct hit scenario of this section applies here also. The area contaminated above 0.5 rem/yr increases from 0.18 ha after 10 years to 330 ha at 1000 years. At and beyond 2000 years, the contaminated areas shrink, mostly as a result of the decay of americium isotopes.

Release to the aquifer due to faulting: Direct hit on waste

Table 6.42 gives the annual dose rates for a faulting event that hits a row of waste canisters when the retardation factor for all nuclides is one. The peak dose rate, 8500 rem/year, almost all from Am-241, first occurs about 200 years after the event at 500 m. After about 2000 years, the Am-241 has decayed to lower levels and Am-243 dominates until 10,000 years. Since all of the nuclides are moving at the same velocity in the aquifer, the percentage at each location is the same.

Table 5.22 presents the annual dose rates for comparison to Table 6.42. The annual dose rates of Table 5.22 are roughly the same over the entire length of the repository at any time up to 1000 years. This is because each point is affected only by the nearest 20 meters. In Table 6.42, the doses at 1000 years vary by a little over a factor of ten. Dose rates throughout are much higher when the retardation factors equal one.

Release to the aquifer due to faulting: Granite tank

Table 6.45 presents the annual dose rates from a fault line intersecting a tank of contaminated repository water in granite. Five percent of the inventory has leached into the tank before the faulting event except for solubility-limited nuclides. Doses rates are very large because of the large tank inventory and the rapid movement of nuclides. The highest dose rate, 12 million rem/yr, is almost all from Am-241. Am-241 dominates until about 2000 years, then Am-243 at 5,000 years, and Pu-239 at 10,000 years.

Release to the aquifer due to shaft seal leakage

Table 6.46 shows the annual dose rates that result from the degradation of the plugged shaft seal. This is modeled similarly to the drilling event, hence the results are similar. The shaft has a cross-sectional area of 25 m^2, vs 0.1 m^2 for a borehole, this allows for higher flow and dose rates. The maximum dose rate is 30,000 rem/yr at 1000 years and 20 meters. Am-241 dominates to about 2000 years after the event, then it decays enough so that Am-243 is dominant to about 10,000 years. Although the shafts begin to deteriorate immediately after sealing, no nuclides are released until the canisters fail at 500 years.

Table 6.41

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Hits Waste
All Retardation Factors Equal One

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.66E+03 AM-241 98.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	2.62E+03 AM-241 98.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	2.50E+03 AM-241 98.1%	1.58E+03 AM-241 98.1%	1.12E+03 AM-241 98.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.31E+03 AM-241 98.0%	1.46E+03 AM-241 98.0%	1.04E+03 AM-241 98.0%	7.36E+02 AM-241 98.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.97E+03 AM-241 97.7%	1.25E+03 AM-241 97.7%	8.84E+02 AM-241 97.7%	6.28E+02 AM-241 97.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.23E+03 AM-241 96.5%	7.78E+02 AM-241 96.5%	5.52E+02 AM-241 96.5%	3.92E+02 AM-241 96.5%	2.51E+02 AM-241 96.5%	2.08E+02 AM-241 96.5%	1.82E+02 AM-241 96.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	5.68E+02 AM-241 93.1%	3.60E+02 AM-241 93.1%	2.55E+02 AM-241 93.1%	1.81E+02 AM-241 93.1%	1.16E+02 AM-241 93.1%	9.61E+01 AM-241 93.1%	8.42E+01 AM-241 93.1%	7.04E+01 AM-241 93.1%	6.25E+01 AM-241 93.1%	0.0 NONE 0.0%
2.00E+03	1.38E+02 AM-241 76.6%	8.72E+01 AM-241 76.6%	6.18E+01 AM-241 76.6%	4.39E+01 AM-241 76.6%	2.82E+01 AM-241 76.6%	2.33E+01 AM-241 76.6%	2.04E+01 AM-241 76.6%	1.71E+01 AM-241 76.6%	1.51E+01 AM-241 76.6%	1.18E+01 AM-241 76.6%
5.00E+03	1.91E+01 AM-243 95.4%	1.21E+01 AM-243 95.4%	8.56E+00 AM-243 95.4%	6.08E+00 AM-243 95.4%	3.90E+00 AM-243 95.4%	3.22E+00 AM-243 95.4%	2.82E+00 AM-243 95.4%	2.36E+00 AM-243 95.4%	2.09E+00 AM-243 95.4%	1.63E+00 AM-243 95.4%
1.00E+04	7.05E+00 AM-243 99.4%	4.46E+00 AM-243 99.4%	3.16E+00 AM-243 99.4%	2.25E+00 AM-243 99.4%	1.44E+00 AM-243 99.5%	1.19E+00 AM-243 99.5%	1.04E+00 AM-243 99.5%	8.73E-01 AM-243 99.5%	7.74E-01 AM-243 99.5%	6.02E-01 AM-243 99.6%

Table 6.42

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
All Retardation Factors Equal One

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.45E+04 AM-241 98.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.45E+04 AM-241 98.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.46E+04 AM-241 98.1%	9.01E+03 AM-241 98.1%	6.14E+03 AM-241 98.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.45E+04 AM-241 98.0%	8.99E+03 AM-241 98.0%	6.15E+03 AM-241 98.0%	4.04E+03 AM-241 98.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.41E+04 AM-241 97.7%	8.79E+03 AM-241 97.7%	6.05E+03 AM-241 97.7%	4.03E+03 AM-241 97.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.19E+04 AM-241 96.5%	7.45E+03 AM-241 96.5%	5.17E+03 AM-241 96.5%	3.52E+03 AM-241 96.5%	1.96E+03 AM-241 96.5%	1.40E+03 AM-241 96.5%	1.03E+03 AM-241 96.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	7.73E+03 AM-241 93.1%	4.86E+03 AM-241 93.1%	3.40E+03 AM-241 93.1%	2.35E+03 AM-241 93.1%	1.38E+03 AM-241 93.1%	1.05E+03 AM-241 93.1%	8.39E+02 AM-241 93.1%	5.63E+02 AM-241 93.1%	3.68E+02 AM-241 93.1%	0.0 NONE 0.0%
2.00E+03	2.90E+03 AM-241 76.6%	1.83E+03 AM-241 76.6%	1.29E+03 AM-241 76.6%	8.98E+02 AM-241 76.6%	5.46E+02 AM-241 76.6%	4.31E+02 AM-241 76.6%	3.60E+02 AM-241 76.6%	2.70E+02 AM-241 76.6%	2.12E+02 AM-241 76.6%	7.45E+01 AM-241 76.6%
5.00E+03	8.50E+02 AM-243 95.5%	5.37E+02 AM-243 95.5%	3.79E+02 AM-243 95.5%	2.66E+02 AM-243 95.5%	1.66E+02 AM-243 95.5%	1.34E+02 AM-243 95.5%	1.15E+02 AM-243 95.5%	9.13E+01 AM-243 95.5%	7.70E+01 AM-243 95.5%	4.78E+01 AM-243 95.5%
1.00E+04	7.08E+02 AM-243 99.9%	4.47E+02 AM-243 99.9%	3.16E+02 AM-243 99.9%	2.23E+02 AM-243 99.9%	1.40E+02 AM-243 99.9%	1.14E+02 AM-243 99.9%	9.80E+01 AM-243 99.9%	7.91E+01 AM-243 99.9%	6.78E+01 AM-243 99.9%	4.56E+01 AM-243 99.9%

Table 6.43

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
All Retardation Factors Equal One

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	4.84E+03 AM-241 98.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	4.80E+03 AM-241 98.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	4.58E+03 AM-241 98.1%	2.90E+03 AM-241 98.1%	2.05E+03 AM-241 98.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	4.23E+03 AM-241 98.0%	2.68E+03 AM-241 98.0%	1.90E+03 AM-241 98.0%	1.35E+03 AM-241 98.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	3.61E+03 AM-241 97.7%	2.28E+03 AM-241 97.7%	1.62E+03 AM-241 97.7%	1.15E+03 AM-241 97.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.25E+03 AM-241 96.5%	1.43E+03 AM-241 96.5%	1.01E+03 AM-241 96.5%	7.18E+02 AM-241 96.5%	4.61E+02 AM-241 96.5%	3.81E+02 AM-241 96.5%	3.34E+02 AM-241 96.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.04E+03 AM-241 93.1%	6.60E+02 AM-241 93.1%	4.68E+02 AM-241 93.1%	3.32E+02 AM-241 93.1%	2.13E+02 AM-241 93.1%	1.76E+02 AM-241 93.1%	1.54E+02 AM-241 93.1%	1.29E+02 AM-241 93.1%	1.15E+02 AM-241 93.1%	0.0 NONE 0.0%
2.00E+03	2.54E+02 AM-241 76.6%	1.61E+02 AM-241 76.6%	1.14E+02 AM-241 76.6%	8.09E+01 AM-241 76.6%	5.14E+01 AM-241 76.6%	4.26E+01 AM-241 76.6%	3.73E+01 AM-241 76.6%	3.13E+01 AM-241 76.6%	2.78E+01 AM-241 76.6%	2.16E+01 AM-241 76.6%
5.00E+03	3.46E+01 AM-243 95.4%	2.20E+01 AM-243 95.4%	1.56E+01 AM-243 95.4%	1.11E+01 AM-243 95.4%	7.11E+00 AM-243 95.4%	5.82E+00 AM-243 95.4%	5.15E+00 AM-243 95.4%	4.29E+00 AM-243 95.5%	3.80E+00 AM-243 95.5%	2.98E+00 AM-243 95.5%
1.00E+04	1.28E+01 AM-243 99.6%	8.11E+00 AM-243 99.6%	5.78E+00 AM-243 99.6%	4.07E+00 AM-243 99.6%	2.63E+00 AM-243 99.6%	2.16E+00 AM-243 99.6%	1.90E+00 AM-243 99.7%	1.58E+00 AM-243 99.7%	1.40E+00 AM-243 99.7%	1.10E+00 AM-243 99.7%

Table 6.44

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Waste Directly Affected
All Retardation Factors Equal One

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.08E+03 AM-241 97.6%	2.14E+03 AM-241 97.6%	2.14E+03 AM-241 97.6%	2.14E+03 AM-241 97.6%	2.14E+03 AM-241 97.6%	2.14E+03 AM-241 97.6%	2.14E+03 AM-241 97.6%	2.14E+03 AM-241 97.6%	2.14E+03 AM-241 97.6%	2.14E+03 AM-241 97.6%
2.00E+01	2.04E+03 AM-241 97.5%	3.23E+03 AM-241 97.5%	3.23E+03 AM-241 97.5%	3.23E+03 AM-241 97.5%	3.23E+03 AM-241 97.5%	3.23E+03 AM-241 97.5%	3.23E+03 AM-241 97.5%	3.23E+03 AM-241 97.5%	3.23E+03 AM-241 97.5%	3.23E+03 AM-241 97.5%
5.00E+01	1.95E+03 AM-241 97.4%	3.41E+03 AM-241 97.4%	5.05E+03 AM-241 97.4%	5.19E+03 AM-241 97.4%	5.19E+03 AM-241 97.4%	5.19E+03 AM-241 97.4%	5.19E+03 AM-241 97.4%	5.19E+03 AM-241 97.4%	5.19E+03 AM-241 97.4%	5.19E+03 AM-241 97.4%
1.00E+02	1.80E+03 AM-241 97.2%	3.15E+03 AM-241 97.2%	4.67E+03 AM-241 97.2%	6.79E+03 AM-241 97.2%	6.97E+03 AM-241 97.2%	6.97E+03 AM-241 97.2%	6.97E+03 AM-241 97.2%	6.97E+03 AM-241 97.2%	6.97E+03 AM-241 97.2%	6.97E+03 AM-241 97.2%
2.00E+02	1.54E+03 AM-241 96.8%	2.70E+03 AM-241 96.8%	3.99E+03 AM-241 96.8%	5.80E+03 AM-241 96.8%	8.58E+03 AM-241 96.8%	8.58E+03 AM-241 96.8%	8.58E+03 AM-241 96.8%	8.58E+03 AM-241 96.8%	8.58E+03 AM-241 96.8%	8.58E+03 AM-241 96.8%
5.00E+02	9.67E+02 AM-241 95.1%	1.69E+03 AM-241 95.1%	2.50E+03 AM-241 95.1%	3.64E+03 AM-241 95.1%	5.89E+03 AM-241 95.1%	7.25E+03 AM-241 95.1%	8.38E+03 AM-241 95.1%	8.58E+03 AM-241 95.1%	8.58E+03 AM-241 95.1%	8.58E+03 AM-241 95.1%
1.00E+03	4.55E+02 AM-241 90.3%	7.95E+02 AM-241 90.3%	1.18E+03 AM-241 90.3%	1.71E+03 AM-241 90.3%	2.77E+03 AM-241 90.3%	3.41E+03 AM-241 90.3%	3.94E+03 AM-241 90.3%	4.81E+03 AM-241 90.3%	5.53E+03 AM-241 90.3%	5.67E+03 AM-241 90.3%
2.00E+03	1.21E+02 AM-241 67.7%	2.11E+02 AM-241 67.7%	3.13E+02 AM-241 67.7%	4.55E+02 AM-241 67.7%	7.36E+02 AM-241 67.7%	9.06E+02 AM-241 67.7%	1.05E+03 AM-241 67.7%	1.28E+03 AM-241 67.7%	1.47E+03 AM-241 67.7%	2.03E+03 AM-241 67.6%
5.00E+03	2.87E+01 AM-243 49.1%	5.02E+01 AM-243 49.1%	7.44E+01 AM-243 49.1%	1.08E+02 AM-243 49.1%	1.75E+02 AM-243 49.0%	2.16E+02 AM-243 49.0%	2.49E+02 AM-243 49.0%	3.05E+02 AM-243 49.0%	3.50E+02 AM-243 48.9%	4.85E+02 AM-243 48.8%
1.00E+04	1.33E+01 AM-243 41.0%	2.32E+01 AM-243 41.0%	3.43E+01 AM-243 41.0%	4.99E+01 AM-243 41.0%	8.08E+01 AM-243 41.0%	9.96E+01 AM-243 40.9%	1.15E+02 AM-243 40.9%	1.41E+02 AM-243 40.9%	1.62E+02 AM-243 40.8%	2.25E+02 AM-243 40.6%

Table 6.45

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement in GRANITE
1000 Years After Repository Sealing

Repository Water Affected
All Retardation Factors Equal One

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.16E+07 AM-241 95.7%	1.26E+07 AM-241 95.7%	1.26E+07 AM-241 95.7%	1.26E+07 AM-241 95.7%	1.26E+07 AM-241 95.7%	1.26E+07 AM-241 95.7%	1.26E+07 AM-241 95.7%	1.26E+07 AM-241 95.7%	1.26E+07 AM-241 95.7%	1.26E+07 AM-241 95.7%
2.00E+01	2.00E+06 AM-241 95.6%	9.35E+06 AM-241 95.6%	9.35E+06 AM-241 95.6%	9.35E+06 AM-241 95.6%	9.35E+06 AM-241 95.6%	9.35E+06 AM-241 95.6%	9.35E+06 AM-241 95.6%	9.35E+06 AM-241 95.6%	9.35E+06 AM-241 95.6%	9.35E+06 AM-241 95.6%
5.00E+01	3.05E+05 AM-241 95.4%	5.78E+05 AM-241 95.4%	3.94E+06 AM-241 95.4%	5.59E+06 AM-241 95.4%	5.59E+06 AM-241 95.4%	5.59E+06 AM-241 95.4%	5.59E+06 AM-241 95.4%	5.59E+06 AM-241 95.4%	5.59E+06 AM-241 95.4%	5.59E+06 AM-241 95.4%
1.00E+02	2.77E+05 AM-241 95.1%	4.85E+05 AM-241 95.1%	7.20E+05 AM-241 95.1%	2.32E+06 AM-241 95.1%	4.13E+06 AM-241 95.1%	4.13E+06 AM-241 95.1%	4.13E+06 AM-241 95.1%	4.13E+06 AM-241 95.1%	4.13E+06 AM-241 95.1%	4.13E+06 AM-241 95.1%
2.00E+02	2.38E+05 AM-241 94.4%	4.16E+05 AM-241 94.4%	6.18E+05 AM-241 94.4%	9.01E+05 AM-241 94.4%	3.18E+06 AM-241 94.4%	3.18E+06 AM-241 94.4%	3.18E+06 AM-241 94.4%	3.18E+06 AM-241 94.4%	3.18E+06 AM-241 94.4%	3.18E+06 AM-241 94.4%
5.00E+02	1.51E+05 AM-241 91.6%	2.64E+05 AM-241 91.6%	3.92E+05 AM-241 91.6%	5.72E+05 AM-241 91.6%	9.34E+05 AM-241 91.6%	1.16E+06 AM-241 91.6%	1.36E+06 AM-241 91.6%	2.14E+06 AM-241 91.6%	2.14E+06 AM-241 91.6%	2.14E+06 AM-241 91.6%
1.00E+03	7.34E+04 AM-241 84.2%	1.28E+05 AM-241 84.2%	1.91E+05 AM-241 84.2%	2.78E+05 AM-241 84.2%	4.54E+05 AM-241 84.2%	5.64E+05 AM-241 84.2%	6.56E+05 AM-241 84.2%	8.14E+05 AM-241 84.2%	9.53E+05 AM-241 84.2%	1.25E+06 AM-241 84.2%
2.00E+03	2.21E+04 AM-241 55.8%	3.86E+04 AM-241 55.8%	5.73E+04 AM-241 55.8%	8.35E+04 AM-241 55.8%	1.36E+05 AM-241 55.8%	1.69E+05 AM-241 55.8%	1.97E+05 AM-241 55.8%	2.45E+05 AM-241 55.9%	2.86E+05 AM-241 55.8%	4.21E+05 AM-241 55.8%
5.00E+03	5.90E+03 AM-243 36.0%	1.03E+04 AM-243 36.0%	1.53E+04 AM-243 36.0%	2.23E+04 AM-243 36.0%	3.65E+04 AM-243 35.9%	4.53E+04 AM-243 36.0%	5.28E+04 AM-243 36.0%	6.55E+04 AM-243 35.9%	7.65E+04 AM-243 35.9%	1.13E+05 AM-243 36.0%
1.00E+04	2.50E+03 PU-239 36.8%	4.38E+03 PU-239 36.8%	6.50E+03 PU-239 36.8%	9.47E+03 PU-239 36.8%	1.55E+04 PU-239 36.8%	1.92E+04 PU-239 36.8%	2.24E+04 PU-239 36.8%	2.78E+04 PU-239 36.8%	3.24E+04 PU-239 36.8%	4.78E+04 PU-239 36.8%

Table 6.46

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Shaft Seal Leakage in GRANITE

All Retardation Factors Equal One

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	9.61E-01 AM-241 98.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	4.04E+01 AM-241 99.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	3.62E+02 AM-241 99.0%	1.07E+02 AM-241 99.0%	2.39E+00 AM-241 99.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.46E+03 AM-241 99.0%	6.70E+02 AM-241 99.0%	2.39E+02 AM-241 99.0%	3.73E+00 AM-241 98.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	5.01E+03 AM-241 98.8%	2.74E+03 AM-241 98.8%	1.48E+03 AM-241 98.8%	5.20E+02 AM-241 98.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.81E+04 AM-241 98.3%	1.09E+04 AM-241 98.3%	7.01E+03 AM-241 98.3%	4.06E+03 AM-241 98.3%	1.16E+03 AM-241 98.3%	3.06E+02 AM-241 98.3%	1.04E+01 AM-241 98.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	2.98E+04 AM-241 96.5%	1.84E+04 AM-241 96.5%	1.24E+04 AM-241 96.5%	8.06E+03 AM-241 96.5%	3.78E+03 AM-241 96.5%	2.29E+03 AM-241 96.5%	1.38E+03 AM-241 96.5%	3.74E+02 AM-241 96.5%	1.18E+01 AM-241 96.5%	0.0 NONE 0.0%
2.00E+03	2.36E+04 AM-241 87.0%	1.48E+04 AM-241 87.0%	1.02E+04 AM-241 87.0%	6.94E+03 AM-241 87.0%	3.86E+03 AM-241 87.0%	2.80E+03 AM-241 87.0%	2.14E+03 AM-241 87.0%	1.31E+03 AM-241 87.0%	8.02E+02 AM-241 87.0%	7.27E+00 AM-241 86.9%
5.00E+03	1.11E+04 AM-243 91.4%	6.96E+03 AM-243 91.4%	4.89E+03 AM-243 91.4%	3.40E+03 AM-243 91.4%	2.06E+03 AM-243 91.4%	1.62E+03 AM-243 91.4%	1.35E+03 AM-243 91.4%	1.01E+03 AM-243 91.4%	8.01E+02 AM-243 91.4%	3.72E+02 AM-243 91.4%
1.00E+04	1.81E+04 AM-243 99.9%	1.14E+04 AM-243 99.9%	8.05E+03 AM-243 99.9%	5.65E+03 AM-243 99.9%	3.50E+03 AM-243 99.9%	2.81E+03 AM-243 99.9%	2.39E+03 AM-243 99.9%	1.88E+03 AM-243 99.9%	1.57E+03 AM-243 99.9%	9.39E+02 AM-243 99.9%

Table 6.47

Area (ha*) of the Aquifer Contaminated
Above the Specified Dose Rate Levels
By Drilling 1000 Years after Sealing

Low retardation factors

Event Description	Length of time after event (yr)	Dose Rate Levels (rem/yr) 0.5	5	50	500	5000
Direct hit on the waste	10-20	0.17	0.15	0.12	0.08	0
	50	1.83	1.54	1.19	0.68	0
	100	5.05	4.21	3.17	1.50	0
	200	4.79	4.15	3.08	1.20	0
	500	51.1	40.5	25.9	0.53	0
	1000	132	97.6	40.3	0.04	0
	2000	303	172	0.67	0	0
	5000	196	2.17	0	0	0
	10000	104	0.07	0	0	0
Drill hits brine pocket	10-20	0.18	0.15	0.12	0.09	0
	50	1.90	1.62	1.29	0.84	0
	100	5.24	4.45	3.47	2.08	0
	200	53.5	43.6	30.4	2.72	0
	500	139	108	61.2	0.25	0
	1000	329	215	4.11	0	0
	2000	234	12.0	0	0	0
	5000	166	0.60	0	0	0
	10000	2.26	0	0	0	0
Drill hits granite tank	10-20	0.18	0.16	0.13	0.09	0.04
	50	1.94	1.68	1.36	0.95	0.08
	100	5.39	4.62	3.69	2.42	0.07
	200	5.37	4.60	3.67	2.39	0.07
	500	55.9	46.5	34.4	13.5	0.02
	1000	148	119	79.2	5.3	0
	2000	363	263	81.9	0.17	0
	5000	298	164	0.48	0	0
	10000	221	2.84	0	0	0
Shaft seal leakage beginning 500 years after closing	10-20	0.18	0.16	0.13	0.09	0.02
	50	1.91	1.64	1.32	0.88	0.03
	100	5.29	4.50	3.54	2.19	0
	200	5.24	4.44	3.47	2.07	0
	500	54.1	44.2	31.4	4.54	0
	1000	141	110	64.6	0.47	0
	2000	332	219	5.09	0	0
	5000	222	6.04	0	0	0
	10000	172	0.75	0	0	0

*1 hectare (ha) = 10^4 square meters

With a retardation factor of 1, the nuclides spread rapidly throughout the aquifer. Table 6.47 shows that the largest contaminated area occurs at 2000 years, 330 ha for dose rates above 0.5 rem/yr.

6.4.2 Higher retardation factors

All of the events with high retardation factors (Tables 6.48 through 6.52) can be discussed in one section because all of the annual dose rates are very small. The americium isotopes which have dominated most of the previous cases, are now held back by the chemical sorption properties of the aquifer strata, taking about 100,000 years to move 20 meters. By this time, Am-243 has decayed very substantially. I-129 and carbon-14 (C-14), with retardation factors equal to one, are the dominant nuclides in drilling releases and remain so for about 1000 years. Np-237 is the dominant isotope later on in Tables 6.51 and 6.52, faulting to aquifers. Pu-239 travels the one-meter distance used as the lower bound for integration in 10,000 years, and produces a highest dose rate of 850 rem/yr, 10,000 years after the faulting event (Table 6.52). Sn-126 and Cs-135 appear in Table 6.49 in the brine pocket release to the aquifer. The shaft seal releases are not listed, they are essentially the same as the drilling hit releases (Table 6.48). Only tank releases as a result of faulting produce dose rates over 100 rem/yr.

Generally speaking, nuclides with low retardation factors are the most important. I-129, C-14, and Np-237 are the dominant nuclides, with very low annual dose rates, for all the drilling events (Tables 6.48, 6.49, and 6.50).

6.5 Effect of a Better-Sealed Borehole

In these scenarios, we assigned the borehole seal an initial permeability of 0.315 m/yr (10^{-6} cm/s) when it was resealed and postulated that the permeability degraded at a rate of 3.15×10^{-4} m/yr^2 (10^{-9} cm/s^2) for a period of 10,000 years. The permeability at any time t is equal to:

$$0.315 + (3.15 \times 10^{-4}\ t).$$

Table 6.48

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Hits Waste
High Retardation Factors

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.33E-05 I -129 71.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	2.33E-05 I -129 71.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	2.31E-05 I -129 71.4%	1.47E-05 I -129 71.4%	1.04E-05 I -129 71.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	8.06E-04 C - 14 97.2%	1.46E-05 I -129 71.6%	1.03E-05 I -129 71.5%	7.36E-06 I -129 71.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	7.89E-04 C - 14 97.1%	1.43E-05 I -129 72.0%	1.02E-05 I -129 71.9%	7.24E-06 I -129 71.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	7.39E-04 C - 14 97.1%	4.74E-04 C - 14 97.1%	3.43E-04 C - 14 97.2%	6.93E-06 I -129 72.7%	4.47E-06 I -129 72.3%	3.72E-06 I -129 71.9%	3.28E-06 I -129 71.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	5.26E-03 NP-237 87.4%	4.25E-04 C - 14 97.0%	3.07E-04 C - 14 97.0%	2.28E-04 C - 14 97.1%	4.19E-06 I -129 73.5%	3.47E-06 I -129 73.3%	3.05E-06 I -129 73.0%	2.57E-06 I -129 72.4%	2.31E-06 I -129 71.5%	0.0 NONE 0.0%
2.00E+03	4.22E-03 NP-237 87.4%	3.42E-04 C - 14 96.6%	2.47E-04 C - 14 96.7%	1.83E-04 C - 14 96.8%	3.75E-06 I -129 74.3%	3.10E-06 I -129 74.3%	2.71E-06 I -129 74.2%	2.27E-06 I -129 74.1%	2.02E-06 I -129 73.9%	1.62E-06 I -129 71.8%
5.00E+03	3.09E-03 NP-237 91.0%	2.14E-03 NP-237 91.6%	2.07E-03 NP-237 93.8%	9.58E-05 C - 14 95.4%	6.95E-05 C - 14 95.9%	6.37E-05 C - 14 96.3%	6.19E-05 C - 14 96.7%	1.71E-06 I -129 73.2%	1.51E-06 I -129 73.4%	1.16E-06 I -129 74.1%
1.00E+04	3.61E-03 NP-237 67.0%	1.63E-03 NP-237 96.2%	1.23E-03 NP-237 96.3%	1.33E-03 NP-237 97.5%	2.40E-05 C - 14 91.9%	2.19E-05 C - 14 92.7%	2.12E-05 C - 14 93.4%	2.17E-05 C - 14 94.7%	2.36E-05 C - 14 95.7%	7.69E-07 I -129 67.9%

Table 6.49

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
High Retardation Factors

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.69E-05 I -129 81.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	3.71E-05 I -129 82.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	3.70E-05 I -129 82.1%	2.34E-05 I -129 82.0%	1.66E-05 I -129 81.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.47E-03 C - 14 97.5%	2.32E-05 I -129 82.2%	1.65E-05 I -129 82.1%	1.17E-05 I -129 82.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.44E-03 C - 14 97.5%	2.29E-05 I -129 82.5%	1.63E-05 I -129 82.4%	1.16E-05 I -129 82.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.35E-03 C - 14 97.4%	8.66E-04 C - 14 97.5%	6.26E-04 C - 14 97.5%	1.11E-05 I -129 83.0%	7.17E-06 I -129 82.7%	5.95E-06 I -129 82.4%	5.23E-06 I -129 82.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	5.81E-03 NP-237 79.2%	7.76E-04 C - 14 97.3%	5.62E-04 C - 14 97.4%	4.16E-04 C - 14 97.5%	6.75E-06 I -129 83.6%	5.59E-06 I -129 83.4%	4.91E-06 I -129 83.2%	4.12E-06 I -129 82.8%	3.69E-06 I -129 82.2%	0.0 NONE 0.0%
2.00E+03	4.66E-03 NP-237 79.0%	6.22E-04 C - 14 97.0%	4.50E-04 C - 14 97.0%	3.35E-04 C - 14 97.2%	6.04E-06 I -129 84.1%	5.00E-06 I -129 84.1%	4.38E-06 I -129 84.1%	3.68E-06 I -129 84.0%	3.27E-06 I -129 83.9%	2.59E-06 I -129 82.3%
5.00E+03	3.31E-03 NP-237 84.7%	2.28E-03 NP-237 85.8%	2.18E-03 NP-237 89.2%	1.73E-04 C - 14 95.9%	1.27E-04 C - 14 96.4%	1.16E-04 C - 14 96.8%	1.13E-04 C - 14 97.1%	2.73E-06 I -129 83.2%	2.41E-06 I -129 83.3%	1.88E-06 I -129 84.0%
1.00E+04	4.59E-03 NP-237 52.6%	1.68E-03 NP-237 93.3%	1.27E-03 NP-237 93.6%	1.35E-03 NP-237 95.6%	4.36E-05 C - 14 93.2%	3.93E-05 C - 14 93.8%	3.80E-05 C - 14 94.4%	3.96E-05 C - 14 95.5%	4.29E-05 C - 14 96.4%	1.20E-06 I -129 79.4%

Table 6.50

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
High Retardation Factors

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	9.72E-05 I -129 93.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	9.87E-05 I -129 93.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.03E-04 I -129 93.6%	6.38E-05 I -129 93.4%	4.36E-05 I -129 93.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	4.41E-03 C - 14 97.5%	6.83E-05 I -129 93.9%	4.68E-05 I -129 93.7%	3.09E-05 I -129 93.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	5.04E-03 C - 14 97.6%	7.67E-05 I -129 94.8%	5.28E-05 I -129 94.6%	3.54E-05 I -129 94.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	6.60E-03 C - 14 97.6%	3.68E-03 C - 14 97.3%	1.96E-03 C - 14 96.5%	4.72E-05 I -129 96.0%	2.64E-05 I -129 95.3%	1.91E-05 I -129 94.5%	1.42E-05 I -129 93.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.31E-02 C - 14 63.4%	5.01E-03 C - 14 97.4%	3.06E-03 C - 14 97.0%	1.37E-03 C - 14 95.3%	3.75E-05 I -129 97.0%	2.87E-05 I -129 96.8%	2.30E-05 I -129 96.4%	1.56E-05 I -129 95.5%	1.04E-05 I -129 93.7%	0.0 NONE 0.0%
2.00E+03	1.45E-02 C - 14 72.6%	6.59E-03 C - 14 97.2%	4.34E-03 C - 14 97.0%	2.58E-03 C - 14 96.5%	5.49E-05 I -129 98.2%	4.34E-05 I -129 98.2%	3.62E-05 I -129 98.1%	2.73E-05 I -129 97.8%	2.15E-05 I -129 97.6%	7.81E-06 I -129 94.2%
5.00E+03	1.49E-02 C - 14 78.1%	9.51E-03 C - 14 76.4%	7.16E-03 C - 14 70.1%	3.51E-03 C - 14 95.9%	1.81E-03 C - 14 95.1%	1.11E-03 C - 14 93.5%	5.15E-04 C - 14 88.1%	4.88E-05 I -129 99.1%	4.11E-05 I -129 99.0%	2.56E-05 I -129 98.8%
1.00E+04	2.23E-02 CS-135 47.0%	7.46E-03 C - 14 73.8%	5.31E-03 C - 14 72.5%	4.15E-03 C - 14 64.2%	1.68E-03 C - 14 92.7%	1.28E-03 C - 14 92.2%	1.01E-03 C - 14 91.5%	6.35E-04 C - 14 89.1%	2.75E-04 C - 14 78.5%	3.99E-05 I -129 99.4%

Table 6.51

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Waste Directly Affected
High Retardation Factors

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.64E-03 TC -99 94.4%	1.69E-03 TC -99 94.5%	1.69E-03 TC -99 94.5%	1.69E-03 TC -99 94.5%	1.69E-03 TC -99 94.5%	1.69E-03 TC -99 94.5%	1.69E-03 TC -99 94.5%	1.69E-03 TC -99 94.5%	1.69E-03 TC -99 94.5%	1.69E-03 TC -99 94.5%
2.00E+01	1.74E-03 TC -99 88.6%	2.65E-03 TC -99 92.2%	2.65E-03 TC -99 92.2%	2.65E-03 TC -99 92.2%	2.65E-03 TC -99 92.2%	2.65E-03 TC -99 92.2%	2.65E-03 TC -99 92.2%	2.65E-03 TC -99 92.2%	2.65E-03 TC -99 92.2%	2.65E-03 TC -99 92.2%
5.00E+01	9.61E-03 NP-237 79.7%	1.08E-02 NP-237 71.1%	1.21E-02 NP-237 63.4%	1.22E-02 NP-237 62.8%	1.22E-02 NP-237 62.8%	1.22E-02 NP-237 62.8%	1.22E-02 NP-237 62.8%	1.22E-02 NP-237 62.8%	1.22E-02 NP-237 62.8%	1.22E-02 NP-237 62.8%
1.00E+02	1.41E-01 NP-237 98.5%	1.43E-01 NP-237 97.7%	1.44E-01 NP-237 96.8%	1.46E-01 NP-237 95.5%	1.46E-01 NP-237 95.4%	1.46E-01 NP-237 95.4%	1.46E-01 NP-237 95.4%	1.46E-01 NP-237 95.4%	1.46E-01 NP-237 95.4%	1.46E-01 NP-237 95.4%
2.00E+02	3.28E-01 NP-237 99.3%	3.29E-01 NP-237 98.9%	3.30E-01 NP-237 98.5%	3.32E-01 NP-237 98.0%	3.35E-01 NP-237 97.1%	3.35E-01 NP-237 97.1%	3.35E-01 NP-237 97.1%	3.35E-01 NP-237 97.1%	3.35E-01 NP-237 97.1%	3.35E-01 NP-237 97.1%
5.00E+02	6.97E-01 NP-237 99.[illegible]%	6.98E-01 NP-237 99.5%	7.00E-01 NP-237 99.2%	7.02E-01 NP-237 99.0%	7.06E-01 NP-237 98.4%	7.08E-01 NP-237 98.1%	7.10E-01 NP-237 97.9%	7.10E-01 NP-237 97.8%	7.10E-01 NP-237 97.8%	7.10E-01 NP-237 97.8%
1.00E+03	1.08E+00 NP-237 99.7%	1.12E+00 NP-237 99.5%	1.12E+00 NP-237 99.4%	1.12E+00 NP-237 99.2%	1.12E+00 NP-237 98.9%	1.13E+00 NP-237 98.7%	1.13E+00 NP-237 98.5%	1.13E+00 NP-237 98.3%	1.13E+00 NP-237 98.1%	1.13E+00 NP-237 98.0%
2.00E+03	1.08E+00 NP-237 99.5%	1.71E+00 NP-237 99.6%	1.71E+00 NP-237 99.5%	1.71E+00 NP-237 99.4%	1.72E+00 NP-237 99.2%	1.72E+00 NP-237 99.1%	1.72E+00 NP-237 99.0%	1.72E+00 NP-237 98.8%	1.72E+00 NP-237 98.7%	1.73E+00 NP-237 98.4%
5.00E+03	1.21E+00 NP-237 89.1%	2.02E+00 NP-237 93.4%	2.92E+00 NP-237 95.4%	3.00E+00 NP-237 95.5%	3.00E+00 NP-237 95.4%	3.00E+00 NP-237 95.4%	3.00E+00 NP-237 95.3%	3.00E+00 NP-237 95.3%	3.00E+00 NP-237 95.2%	3.01E+00 NP-237 95.1%
1.00E+04	1.86E+00 NP-237 51.7%	2.50E+00 NP-237 64.1%	3.09E+00 NP-237 71.0%	3.69E+00 NP-237 75.6%	3.73E+00 NP-237 75.9%	3.73E+00 NP-237 75.8%	3.73E+00 NP-237 75.8%	3.74E+00 NP-237 75.8%	3.74E+00 NP-237 75.8%	3.74E+00 NP-237 75.7%

Table 6.52

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement in GRANITE
1000 Years After Repository Sealing

Repository Water Affected
High Retardation Factors

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	9.87E+00 TC -99 92.7%	1.06E+01 TC -99 92.5%	1.06E+01 TC -99 92.5%	1.06E+01 TC -99 92.5%	1.06E+01 TC -99 92.5%	1.06E+01 TC -99 92.5%	1.06E+01 TC -99 92.5%	1.06E+01 TC -99 92.5%	1.06E+01 TC -99 92.5%	1.06E+01 TC -99 92.5%
2.00E+01	2.38E+00 TC -99 66.4%	8.26E+00 TC -99 89.8%	8.26E+00 TC -99 89.8%	8.26E+00 TC -99 89.8%	8.26E+00 TC -99 89.8%	8.26E+00 TC -99 89.8%	8.26E+00 TC -99 89.8%	8.26E+00 TC -99 89.8%	8.26E+00 TC -99 89.8%	8.26E+00 TC -99 89.8%
5.00E+01	2.28E+02 NP-237 99.7%	2.29E+02 NP-237 99.6%	2.32E+02 NP-237 98.4%	2.33E+02 NP-237 97.8%	2.33E+02 NP-237 97.8%	2.33E+02 NP-237 97.8%	2.33E+02 NP-237 97.8%	2.33E+02 NP-237 97.8%	2.33E+02 NP-237 97.8%	2.33E+02 NP-237 97.8%
1.00E+02	5.00E+02 NP-237 99.9%	5.00E+02 NP-237 99.8%	5.00E+02 NP-237 99.8%	5.02E+02 NP-237 99.5%	5.03E+02 NP-237 99.2%	5.03E+02 NP-237 99.2%	5.03E+02 NP-237 99.2%	5.03E+02 NP-237 99.2%	5.03E+02 NP-237 99.2%	5.03E+02 NP-237 99.2%
2.00E+02	4.34E+02 NP-237 99.9%	4.35E+02 NP-237 99.8%	4.35E+02 NP-237 99.8%	4.35E+02 NP-237 99.7%	4.37E+02 NP-237 99.2%	4.37E+02 NP-237 99.2%	4.37E+02 NP-237 99.2%	4.37E+02 NP-237 99.2%	4.37E+02 NP-237 99.2%	4.37E+02 NP-237 99.2%
5.00E+02	4.53E+02 NP-237 99.9%	4.53E+02 NP-237 99.9%	4.53E+02 NP-237 99.8%	4.54E+02 NP-237 99.7%	4.54E+02 NP-237 99.6%	4.55E+02 NP-237 99.5%	4.55E+02 NP-237 99.4%	4.56E+02 NP-237 99.2%	4.56E+02 NP-237 99.2%	4.56E+02 NP-237 99.2%
1.00E+03	3.87E+02 NP-237 99.8%	5.38E+02 NP-237 99.8%	5.38E+02 NP-237 99.7%	5.38E+02 NP-237 99.7%	5.39E+02 NP-237 99.6%	5.39E+02 NP-237 99.5%	5.40E+02 NP-237 99.4%	5.40E+02 NP-237 99.4%	5.41E+02 NP-237 99.3%	5.42E+02 NP-237 99.1%
2.00E+03	3.51E+02 NP-237 99.7%	6.72E+02 NP-237 99.8%	6.72E+02 NP-237 99.8%	6.73E+02 NP-237 99.7%	6.73E+02 NP-237 99.6%	6.74E+02 NP-237 99.6%	6.74E+02 NP-237 99.5%	6.74E+02 NP-237 99.5%	6.75E+02 NP-237 99.4%	6.76E+02 NP-237 99.2%
5.00E+03	4.65E+02 NP-237 55.6%	6.84E+02 NP-237 69.8%	9.79E+02 NP-237 78.9%	1.07E+03 NP-237 80.7%	1.07E+03 NP-237 80.6%	1.07E+03 NP-237 80.6%	1.07E+03 NP-237 80.6%	1.07E+03 NP-237 80.6%	1.07E+03 NP-237 80.5%	1.07E+03 NP-237 80.5%
1.00E+04	8.58E+02 PU-239 31.9%	9.91E+02 NP-237 29.2%	1.17E+03 NP-237 40.0%	1.53E+03 NP-237 54.3%	1.61E+03 NP-237 56.5%	1.61E+03 NP-237 56.5%	1.61E+03 NP-237 56.4%	1.61E+03 NP-237 56.4%	1.61E+03 NP-237 56.4%	1.61E+03 NP-237 56.4%

In the base case, the permeability was 31.5 m/yr, which is always higher than the permeability in this section. The high permeability in the base case corresponds to very poor resealing of the borehole, perhaps even to the permeability that would result from natural plugging of an unsealed borehole with rock and dirt.

Changing the permeability of the borehole seal from the repository to the aquifer affects only drilling releases. It affects all releases from repository water because the permeability of the release path affects the flow of repository water and, therefore, the rate at which nuclides reach the groundwater. In direct hits, it affects only the solubility-limited nuclides because the model equations for leach-limited nuclides do not include a flow term.

6.5.1 Direct hit on waste

Table 6.53 gives the annual dose rates for a direct hit on waste. These values can be compared with those of Table 5.7. All of the dose rates in Table 6.53 are equal to or less than those in Table 5.7 because the permeability is smaller in the direct hit drilling. Contaminated areas are the same (Tables 5.11 and 6.56).

6.5.2 Granite tank

Table 6.54 gives annual dose rates for releases from the granite tank. These annual dose rates can be compared with those of Table 5.17, for the same base case event. For example, the maximum dose rate in Table 6.54 is 70 rem/yr (at 10,000 years) versus 1830 rem/yr (at 1000 years) in Table 5.17. The dose rate in Table 6.54 is about a factor of 25 less due to the lower permeability and its consequential longer decay time.

The permeability applying to a dose at 10 meters and the 1000-year dose time is the permeability 48 years after drilling, since borehole permeability begins to degrade immediately after the borehole is resealed, or 0.33 m/yr. The permeability for the base case is 31.5 m/yr. The ratio of the permeabilities is 31.5/0.33 or about 95. So, the dose

Table 6.53

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Hits Waste
Better-sealed Borehole

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.96E-03 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.96E-03 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.95E-03 CS-135 58.8%	1.23E-03 CS-135 58.8%	8.74E-04 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.42E-02 SN-126 92.0%	1.22E-03 CS-135 58.9%	8.67E-04 CS-135 58.9%	6.16E-04 CS-135 58.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	2.40E-02 SN-126 92.1%	1.21E-03 CS-135 59.2%	8.54E-04 CS-135 59.2%	6.07E-04 CS-135 59.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.32E-02 SN-126 92.1%	1.49E-02 SN-126 92.2%	1.07E-02 SN-126 92.4%	5.81E-04 CS-135 60.1%	3.72E-04 CS-135 60.1%	3.08E-04 CS-135 60.1%	2.70E-04 CS-135 60.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	6.25E+02 AM-241 93.1%	1.41E-02 SN-126 92.4%	1.02E-02 SN-126 92.5%	7.52E-03 SN-126 92.8%	3.46E-04 CS-135 61.5%	2.86E-04 CS-135 61.5%	2.51E-04 CS-135 61.5%	2.10E-04 CS-135 61.5%	1.86E-04 CS-135 61.5%	0.0 NONE 0.0%
2.00E+03	1.51E+02 AM-241 76.6%	1.26E-02 SN-126 92.6%	9.11E-03 SN-126 92.8%	6.74E-03 SN-126 93.1%	3.00E-04 CS-135 64.2%	2.48E-04 CS-135 64.2%	2.17E-04 CS-135 64.2%	1.82E-04 CS-135 64.2%	1.61E-04 CS-135 64.2%	1.25E-04 CS-135 64.2%
5.00E+03	2.09E+01 AM-243 95.5%	1.53E+01 AM-243 95.5%	1.37E+01 AM-243 95.6%	4.86E-03 SN-126 93.6%	3.52E-03 SN-126 94.4%	3.22E-03 SN-126 94.9%	3.12E-03 SN-126 95.4%	1.20E-04 CS-135 71.8%	1.07E-04 CS-135 71.8%	8.29E-05 CS-135 71.8%
1.00E+04	7.71E+00 AM-243 99.9%	5.63E+00 AM-243 99.9%	5.05E+00 AM-243 99.9%	5.74E+00 AM-243 99.9%	2.05E-03 SN-126 94.9%	1.88E-03 SN-126 95.4%	1.82E-03 SN-126 95.8%	1.87E-03 SN-126 96.6%	2.04E-03 SN-126 97.2%	4.41E-05 CS-135 81.9%

Table 6.54

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
Better-sealed Borehole

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.07E-04 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.10E-04 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.18E-04 CS-135 58.8%	7.21E-05 CS-135 58.8%	4.79E-05 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.36E-03 SN-126 90.3%	8.11E-05 CS-135 58.9%	5.42E-05 CS-135 58.9%	3.40E-05 CS-135 58.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.73E-03 SN-126 90.6%	9.99E-05 CS-135 59.2%	6.73E-05 CS-135 59.2%	4.30E-05 CS-135 59.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	2.96E-03 SN-126 91.1%	1.51E-03 SN-126 89.2%	6.88E-04 SN-126 83.8%	7.33E-05 CS-135 60.1%	3.66E-05 CS-135 60.1%	2.38E-05 CS-135 60.1%	1.57E-05 CS-135 60.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	3.86E+01 AM-241 93.1%	3.00E-03 SN-126 90.5%	1.63E-03 SN-126 87.9%	5.64E-04 SN-126 76.4%	7.23E-05 CS-135 61.5%	5.13E-05 CS-135 61.5%	3.81E-05 CS-135 61.5%	2.15E-05 CS-135 61.5%	1.15E-05 CS-135 61.5%	0.0 NONE 0.0%
2.00E+03	4.35E+01 AM-241 76.6%	6.83E-03 SN-126 91.5%	4.16E-03 SN-126 90.3%	2.08E-03 SN-126 86.7%	1.61E-04 CS-135 64.2%	1.21E-04 CS-135 64.2%	9.66E-05 CS-135 64.2%	6.57E-05 CS-135 64.2%	4.63E-05 CS-135 64.2%	8.68E-06 CS-135 64.2%
5.00E+03	3.88E+01 AM-243 95.5%	1.42E+01 AM-243 95.5%	1.25E+00 AM-243 98.5%	9.25E-03 SN-126 91.3%	3.58E-03 SN-126 86.4%	1.64E-03 SN-126 76.5%	6.03E-04 SN-126 46.4%	2.46E-04 CS-135 71.8%	1.98E-04 CS-135 71.8%	9.97E-05 CS-135 71.8%
1.00E+04	6.81E+01 AM-243 99.9%	3.42E+01 AM-243 99.8%	1.48E+01 AM-243 99.7%	8.37E-01 AM-243 97.0%	1.29E-02 SN-126 91.4%	8.59E-03 SN-126 89.6%	5.85E-03 SN-126 87.1%	2.52E-03 SN-126 76.3%	7.81E-04 CS-135 52.4%	3.04E-04 CS-135 81.9%

rate at 1000 years due to Am-241 is a factor of 95 less in this scenario than the base case -- 1830/95 = 19 rem/yr. The same isotopes dominate practically all the same locations on Tables 5.17 and 6.54. As the dose time increases, the value of the permeability approaches the base case value and so the annual dose rates converge. The area tables 5.21 and 6.56 are zero until a dose time of 1000 years. There are no dose rates over 19.2 rem/yr for this event.

6.5.3 Brine pocket

The small size of the brine pocket and the solubility limit of the americium produce interesting results. With a high, constant permeability (base case) there is a very high flow rate and many turnovers of the brine water per year. With this quick turnover rate which never allows the americium to reach its solubility limit, the results are approximately the same as those from a direct hit on two waste canisters. However, when looking at a small, degrading permeability, the outcome is much different. Since the flow rate is much lower, the turnover rate is longer and the Am-241 reaches its solubility limit of 160 Ci/m^3 in about 50 years. As time increases, the permeability and flow increase. The concentration remains at 160 Ci/m^3 in the brine pocket until decay reduces the source term to lower levels. Therefore, the americium release rate increases with time.

At a dose time of 1000 years, when the Am-241 has traveled 20 meters, the dose rate due to the lower permeability is 3200 rem/yr, 80% from Am-241. This is about 3 times higher than the base case. The values in the annual dose rate tables converge as the dose time increases (Tables 5.12 and 6.55). Contaminated areas are presented on Table 6.56, they are slightly larger than the base case (Table 5.16).

6.6 Effect of Varying the Groundwater Velocity

The effects of two different groundwater velocities were examined, 0.21 m/yr and 21 m/yr. These values are a factor of 10 lower and higher, respectively, than the base case value of 2.1 m/yr. Each

Table 6.55

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
Better-sealed Borehole

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.83E-04 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	4.71E-03 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	2.89E-02 CS-135 58.8%	9.52E-03 CS-135 58.8%	4.21E-04 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.50E-01 CS-135 50.2%	5.68E-02 CS-135 58.9%	1.99E-02 CS-135 58.9%	6.16E-04 CS-135 58.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	6.37E-01 CS-135 56.6%	3.34E-01 CS-135 59.2%	1.76E-01 CS-135 59.2%	5.51E-02 CS-135 59.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.11E-01 CS-135 41.8%	8.29E-02 CS-135 45.7%	8.02E-02 CS-135 51.0%	1.01E-01 CS-135 60.1%	1.70E-01 CS-135 60.1%	5.52E-02 CS-135 60.1%	1.82E-03 CS-135 60.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	3.25E+03 AM-241 80.5%	2.95E-02 SN-126 84.0%	1.93E-02 SN-126 82.2%	1.13E-02 SN-126 77.3%	2.00E-03 CS-135 61.5%	2.18E-03 CS-135 61.5%	5.91E-03 CS-135 61.5%	9.45E-02 CS-135 61.5%	3.61E-03 CS-135 61.5%	0.0 NONE 0.0%
2.00E+03	6.[illegible]6E+02 AM-241 76.6%	3.58E-02 SN-126 93.0%	2.42E-02 SN-126 92.6%	1.49E-02 SN-126 91.4%	8.56E-04 CS-135 64.2%	7.36E-04 CS-135 64.2%	6.76E-04 CS-135 64.2%	6.35E-04 CS-135 64.2%	6.65E-04 CS-135 64.2%	9.25E-03 CS-135 64.2%
5.00E+03	4.33E+01 AM-243 95.5%	3.61E+01 AM-243 95.6%	2.29E+02 AM-243 98.2%	1.00E-02 SN-126 93.9%	8.26E-03 SN-126 95.2%	8.12E-03 SN-126 95.9%	4.54E-03 SN-126 93.6%	2.46E-04 CS-135 71.8%	2.21E-04 CS-135 71.8%	1.85E-04 CS-135 71.8%
1.00E+04	1.43E+01 AM-243 99.9%	1.06E+01 AM-243 99.9%	9.92E+00 AM-243 99.9%	1.16E+02 AM-243 100.0%	3.85E-03 SN-126 94.9%	3.58E-03 SN-126 95.5%	3.57E-03 SN-126 96.0%	4.27E-03 SN-126 97.2%	3.37E-03 SN-126 96.9%	8.25E-05 CS-135 81.9%

Table 6.56

Area (ha*) of the Aquifer Contaminated
Above the Specified Dose Rate Levels
Following Drilling 1000 Years after Sealing

K' = 3.15×10^{-4} (better seal)

Event description	Length of time after event (yr)	Dose Rate Levels (rem/yr) 0.5	5	50	500
Direct hit on the waste	0-500	0	0	0	0
	1000	0.33	0.27	0.20	0.06
	2000	0.30	0.23	0.13	0
	5000	2.09	1.18	0	0
	10000	6.08	1.28	0	0
Drill hits granite tank	0-500	0	0	0	0
	1000	0.24	0.14	0	0
	2000	0.23	0.14	0	0
	5000	0.87	0.07	0	0
	10000	1.36	0	0	0
Drill hits pocket brine	0-500	0	0	0	0
	1000	0.36	0.31	0.25	0.16
	2000	0.32	0.26	0.18	0
	5000	2.44	1.72	0.30	0
	10000	7.34	4.30	0	0
Shaft seal release	0-500	0	0	0	0
	1000	0.35	0.29	0.22	0.12
	2000	0.31	0.25	0.16	0
	5000	2.12	1.23	0	0
	10000	6.16	1.65	0	0

*1 hectare (ha) = 10^4 square meters

event will be examined in a separate section of this chapter. The concentration at a given point and time in the aquifer is inversely proportional to v, but the nuclides will reach a given point at a different time.

When the groundwater velocity is 21 m/yr, nuclides with a retardation factor of one or ten arrive at the 20-meter distance within ten years after drilling. Nuclides with a retardation factor of 100, such as the americium isotopes, travel 20 meters in 95 years, and so appear at this distance at the 100-year dose time, rather than at the 1000-year dose time. The large annual dose rates associated with Am-241 therefore occur earlier than they do with the base case velocity of 2.1 m/yr. When the groundwater velocity is 0.21 m/yr, no nuclides travel 20 meters until 95 years, so the tables show no dose rates before this time. Am-241 does not travel 20 meters until 9500 years, by which time it has decayed by a factor of almost two million, and so is never an important contributor to any dose rates.

6.6.1 Release to the aquifer due to drilling

Direct hit on waste

Tables 6.57, 5.7 and 6.58 show dose rates for a direct hit drilling release with groundwater velocities of 21, 2.1, and 0.21 m/yr, respectively. The maximum dose rates occur at 20 meters in all cases. Table 6.57 shows Sn-126 dominant at 20 meters until a dose time of 100 years when the Am-241 overshadows it. The peak americium dose rate is 230 rem/yr in Table 6.57 compared to 580 rem/yr (93% of 625 rem/yr) in Table 5.7 at 1000 years. Am-241 dominates until a dose time of 5000 years when Am-243 becomes the major contributor. Further downstream is Sn-126 slowly meandering through the porous media. The doses at later years are lower than the base case due to diffusion.

Table 6.58 is the same event with an aquifer velocity of 0.21 m/yr. For this scenario no nuclides reach the 20-meter distance until 100 years after drilling. Sn-126 and Cs-135 dominate before 10,000 years, however, the doses rates are all a fraction of a rem/yr. Higher dose rates appear at 10,000 years, when Am-243 has traveled 20 meters.

Am-241 is never important because of decay in the aquifer to travel 20 meters. The largest dose rate, 180 rem/yr, occurs at 20 meters and 10,000 years.

Table 6.69 shows the contaminated areas corresponding to Tables 6.57 and 6.58. When the aquifer is flowing at the high rate of 21 m/yr, dose rate levels reach above 0.5 rem/yr at a dose time of 100 years. Before 100 years, all areas are zero. The contaminated areas increase markedly with time as all the nuclides spread throughout the aquifer. The aquifer is contaminated above 0.5 rem/yr until the 10,000-year dose time. For the slow-moving aquifer (0.21 m/yr), the entire aquifer is below the lower dose limit of 0.5 rem/yr until the 10,000-year dose time. The contaminated area is a factor of thirty smaller than that associated with the fast aquifer.

Granite tank

The next two tables (6.59 and 6.60) show annual dose rates from drilling into a granite repository when the groundwater velocities are 21 m/yr or 0.21 m/yr, respectively. The base case results were given in Table 5.17, where the velocity was 2.1 m/yr. The highest dose rates are from the two americium isotopes. Am-241 gives 98% of a 1280 rem/yr dose rate when v = 21 m/yr, 100 years after the drilling event. After 5000 years, Am-243 gives the highest dose rate. Farther downstream the nuclides Sn-126 and Cs-135 dominate. Table 6.60 shows that the 100-year dose time is the first time any nuclides have traveled 20 meters in the slow-moving aquifer.

The areas contaminated are displayed in Table 6.69. Table 6.69 shows that areas of the fast-moving aquifer become contaminated above 0.5 rem/yr 100 years after the event. This is from the Am-241 that has traveled into the aquifer. As the dose time increases, the cumulative areas above the given dose rate levels increase through 1000 years, then begin to decrease at 2000 years; however, the 0.5-rem/yr level area increases through 10,000 years. The slow-moving aquifer areas are displayed in Table 6.69. No areas are contaminated above 0.5 rem/yr

Table 6.57

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Hits Waste
High Aquifer Velocity

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.43E-03 SN-126 91.9%	1.24E-04 CS-135 58.5%	8.78E-05 CS-135 58.5%	6.21E-05 CS-135 58.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	2.43E-03 SN-126 91.9%	1.24E-04 CS-135 58.5%	8.77E-05 CS-135 58.5%	6.20E-05 CS-135 58.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	2.42E-03 SN-126 91.9%	1.53E-03 SN-126 91.9%	1.09E-03 SN-126 92.0%	6.17E-05 CS-135 58.6%	3.91E-05 CS-135 58.6%	3.20E-05 CS-135 58.6%	2.77E-05 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	2.33E+02 AM-241 98.0%	1.52E-03 SN-126 92.0%	1.08E-03 SN-126 92.0%	7.66E-04 SN-126 92.0%	3.88E-05 CS-135 58.7%	3.17E-05 CS-135 58.7%	2.75E-05 CS-135 58.7%	2.25E-05 CS-135 58.7%	1.95E-05 CS-135 58.7%	0.0 NONE 0.0%
2.00E+02	1.99E+02 AM-241 97.7%	1.51E-03 SN-126 92.0%	1.07E-03 SN-126 92.0%	7.58E-04 SN-126 92.0%	3.82E-05 CS-135 59.0%	3.13E-05 CS-135 59.0%	2.71E-05 CS-135 59.0%	2.22E-05 CS-135 59.0%	1.93E-05 CS-135 59.0%	1.37E-05 CS-135 59.0%
5.00E+02	1.24E+02 AM-241 96.5%	7.95E+01 AM-241 96.5%	5.76E+01 AM-241 96.5%	7.33E-04 SN-126 92.1%	4.70E-04 SN-126 92.2%	3.88E-04 SN-126 92.3%	3.40E-04 SN-126 92.4%	2.12E-05 CS-135 59.9%	1.84E-05 CS-135 59.9%	1.31E-05 CS-135 59.9%
1.00E+03	5.73E+01 AM-241 93.1%	3.68E+01 AM-241 93.1%	2.66E+01 AM-241 93.1%	1.98E+01 AM-241 93.1%	4.45E-04 SN-126 92.4%	3.67E-04 SN-126 92.4%	3.22E-04 SN-126 92.5%	2.69E-04 SN-126 92.7%	2.38E-04 SN-126 92.8%	1.22E-05 CS-135 61.3%
2.00E+03	1.39E+01 AM-241 76.6%	8.91E+00 AM-241 76.6%	6.45E+00 AM-241 76.6%	4.79E+00 AM-241 76.6%	3.99E-04 SN-126 92.6%	3.29E-04 SN-126 92.7%	2.88E-04 SN-126 92.8%	2.41E-04 SN-126 92.9%	2.13E-04 SN-126 93.0%	1.65E-04 SN-126 93.6%
5.00E+03	1.92E+00 AM-243 95.4%	1.23E+00 AM-243 95.4%	8.93E-01 AM-243 95.4%	6.62E-01 AM-243 95.4%	4.83E-01 AM-243 95.4%	4.44E-01 AM-243 95.4%	4.33E-01 AM-243 95.4%	1.74E-04 SN-126 93.5%	1.54E-04 SN-126 93.6%	1.19E-04 SN-126 94.1%
1.00E+04	7.11E-01 AM-243 99.4%	4.56E-01 AM-243 99.5%	3.30E-01 AM-243 99.5%	2.45E-01 AM-243 99.5%	1.78E-01 AM-243 99.6%	1.64E-01 AM-243 99.7%	1.60E-01 AM-243 99.7%	1.66E-01 AM-243 99.8%	1.82E-01 AM-243 99.8%	6.93E-05 SN-126 94.6%

Table 6.58

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling
1000 Years After Repository Sealing

Drill Hits Waste
Low Aquifer Velocity

TIME (yr)	DISTANCE (meters) 20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.95E-02 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.93E-02 CS-135 59.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.84E-02 CS-135 59.9%	1.18E-02 CS-135 59.9%	8.56E-03 CS-135 59.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	2.38E-01 SN-126 92.8%	1.10E-02 CS-135 61.3%	7.95E-03 CS-135 61.3%	5.90E-03 CS-135 61.3%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+03	2.13E-01 SN-126 93.0%	9.51E-03 CS-135 64.0%	6.89E-03 CS-135 64.0%	5.11E-03 CS-135 64.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+03	1.54E-01 SN-126 93.6%	1.11E-01 SN-126 94.3%	9.87E-02 SN-126 95.4%	3.38E-03 CS-135 71.6%	2.47E-03 CS-135 71.6%	2.27E-03 CS-135 71.6%	2.21E-03 CS-135 71.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+04	1.82E+02 AM-243 99.8%	6.49E-02 SN-126 94.8%	5.76E-02 SN-126 95.8%	6.46E-02 SN-126 97.2%	1.31E-03 CS-135 81.5%	1.21E-03 CS-135 81.5%	1.18E-03 CS-135 81.5%	1.22E-03 CS-135 81.6%	1.34E-03 CS-135 81.6%	0.0 NONE 0.0%

Table 6.59

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
High Aquifer Velocity

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	1.33E-02 SN-126 91.8%	6.84E-04 CS-135 58.6%	4.82E-04 CS-135 58.6%	3.38E-04 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	1.35E-02 SN-126 91.8%	6.94E-04 CS-135 58.7%	4.89E-04 CS-135 58.7%	3.43E-04 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	1.41E-02 SN-126 91.9%	8.74E-03 SN-126 91.7%	5.97E-03 SN-126 91.4%	3.59E-04 CS-135 58.8%	2.22E-04 CS-135 58.8%	1.78E-04 CS-135 58.8%	1.51E-04 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.28E+03 AM-241 98.0%	9.39E-03 SN-126 91.7%	6.44E-03 SN-126 91.5%	4.26E-03 SN-126 91.0%	2.38E-04 CS-135 58.9%	1.91E-04 CS-135 58.9%	1.63E-04 CS-135 58.9%	1.28E-04 CS-135 58.9%	1.07E-04 CS-135 58.9%	0.0 NONE 0.0%
2.00E+02	1.27E+03 AM-241 97.7%	1.06E-02 SN-126 91.8%	7.33E-03 SN-126 91.6%	4.91E-03 SN-126 91.2%	2.69E-04 CS-135 59.2%	2.16E-04 CS-135 59.2%	1.85E-04 CS-135 59.2%	1.47E-04 CS-135 59.2%	1.23E-04 CS-135 59.2%	7.59E-05 CS-135 59.2%
5.00E+02	1.11E+03 AM-241 96.5%	6.19E+02 AM-241 96.5%	3.27E+02 AM-241 96.5%	6.63E-03 SN-126 91.6%	3.73E-03 SN-126 90.6%	2.70E-03 SN-126 89.5%	2.02E-03 SN-126 88.0%	1.94E-04 CS-135 60.1%	1.65E-04 CS-135 60.1%	1.07E-04 CS-135 60.1%
1.00E+03	7.42E+02 AM-241 93.1%	4.36E+02 AM-241 93.1%	2.65E+02 AM-241 93.1%	1.16E+02 AM-241 93.1%	5.32E-03 SN-126 91.4%	4.08E-03 SN-126 90.9%	3.28E-03 SN-126 90.3%	2.25E-03 SN-126 88.5%	1.52E-03 SN-126 85.5%	1.49E-04 CS-135 61.5%
2.00E+03	2.84E+02 AM-241 76.6%	1.73E+02 AM-241 76.6%	1.14E+02 AM-241 76.6%	6.72E+01 AM-241 76.6%	7.78E-03 SN-126 92.1%	6.15E-03 SN-126 91.8%	5.14E-03 SN-126 91.6%	3.89E-03 SN-126 91.0%	3.09E-03 SN-126 90.2%	1.18E-03 SN-126 82.4%
5.00E+03	8.43E+01 AM-243 95.5%	5.26E+01 AM-243 95.5%	3.63E+01 AM-243 95.5%	2.43E+01 AM-243 95.5%	1.24E+01 AM-243 95.5%	7.44E+00 AM-243 96.3%	3.15E+00 AM-243 99.5%	6.78E-03 SN-126 92.7%	5.72E-03 SN-126 92.5%	3.59E-03 SN-126 91.6%
1.00E+04	7.05E+01 AM-243 99.9%	4.43E+01 AM-243 99.9%	3.10E+01 AM-243 99.9%	2.14E+01 AM-243 99.9%	1.25E+01 AM-243 99.9%	9.49E+00 AM-243 99.9%	7.48E+00 AM-243 99.8%	4.56E+00 AM-243 99.8%	1.75E+00 AM-243 99.5%	5.35E-03 SN-126 93.2%

Table 6.60

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in GRANITE
1000 Years After Repository Sealing

Drill Hits Repository Water
Low Aquifer Velocity

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.07E-01 CS-135 58.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	1.23E-01 CS-135 59.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	1.65E-01 CS-135 60.1%	9.18E-02 CS-135 60.1%	4.84E-02 CS-135 60.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.52E+00 SN-126 85.5%	1.30E-01 CS-135 61.5%	7.90E-02 CS-135 61.5%	3.47E-02 CS-135 61.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+03	3.09E+00 SN-126 90.2%	1.84E-01 CS-135 64.2%	1.21E-01 CS-135 64.2%	7.15E-02 CS-135 64.2%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+03	5.72E+00 SN-126 92.5%	2.97E+00 SN-126 91.0%	8.99E-01 SN-126 79.4%	1.24E-01 CS-135 71.8%	6.34E-02 CS-135 71.3%	3.82E-02 CS-135 71.8%	1.67E-02 CS-135 71.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+04	1.75E+03 AM-243 99.5%	4.66E+00 SN-126 93.0%	2.81E+00 SN-126 91.9%	7.59E-01 SN-126 79.3%	9.21E-02 CS-135 81.9%	6.96E-02 CS-135 81.9%	5.49E-02 CS-135 81.9%	3.35E-02 CS-135 81.9%	1.28E-02 CS-135 81.9%	0.0 NONE 0.0%

until 1000 years, this is when Sn-126 has moved 20 meters to give dose rates over 0.5 rem/yr. At 10,000 years the dose rates increase greatly due to the presence of Am-243. The slower aquifer produces smaller, but longer lasting dose rates.

Brine pocket

Table 6.61 gives the annual dose rates for the brine pocket drilling release to the aquifer with a groundwater velocity of 21 m/yr. Sn-126 and Cs-135 dominate until about 100 years, when Am-241 first appears, giving a dose rate of 420 rem/yr. Table 5.12 gave the base case (2.1 m/yr) results, with a maximum dose of 1150 rem/yr (93% from Am-241). The faster flow rate causes greater diffusion and, therefore, the peak dose rate to be lower. As Am-241 spreads and decays in time, it falls from its peak dose rate of 420 rem/yr. By 5000 years, Am-243 has replaced Am-241 as the dominant nuclide. Table 6.62 presents the dose rates for a slow-moving aquifer, in which no nuclides travel 20 meters until 100 years. Sn-126 and Cs-135 control all dose rates until Am-243 appears at 10,000 years. Table 6.69 shows the contaminated areas from the event at the two groundwater velocities. The faster flow rate produces a larger and longer contaminated area than the base case (Table 5.16) with the converse being true for the slower flow rate.

6.6.2 Release to the aquifer due to faulting

Direct hit on waste

Tables 6.63 and 6.64 are faulting event tables with aquifer velocities of 21 m/yr and 0.21 m/yr, respectively. Am-241 travels the one-meter distance which is the lower bound for integration 10 years after the fault has opened in the fast-moving aquifer. The dose rate builds up from 27 rem/yr at 10 years to 160 rem/yr at 200 years. As the Am-241 decays, Am-243 becomes the dominant nuclide at a dose time of 5000 years. The slower aquifer of Table 6.64 does not become saturated with Am-241 until 500 years after the event. Am-243 dominates later when the Am-241 has decayed. The annual dose rates in later years are higher than the base case since the nuclides have not diffused as much as in the base case, shown in Table 5.22.

Contaminated repository water

Tables 6.65 and 6.66 show the annual dose rates from a fault line releasing nuclides from contaminated repository water strata. Table 6.66 has a groundwater velocity of 0.21 m/yr and a diffusion constant of 1.26 m/yr^2. Tc-99 and Sn-126 dominate the table until 500 years. The maximum dose rate before the Am-241 has traveled one meter (lower bound on the integral) is 40 rem/yr. Am-241 appears at 500 years and is dominant through 2000 years. The peak dose rate in the table, 180,000 rem/yr, occurs at 1000 years. After 5000 years, Am-243 becomes the dominant nuclide.

Annual dose rates from the fast-moving aquifer system are dominated by Am-241 until 5000 years. The maximum dose rate occurs at 10 years and is a factor of two larger than in the slowing-moving aquifer scenario. At 5000 years, Am-243 dominates as the largest contributor but it is replaced by Pu-239 at 10,000 years.

6.6.3 Release to the aquifer due to shaft seal leakage

Tables 6.67 and 6.68 are annual dose rate tables for releases through the shaft seals. Table 6.69 is the contaminated area table for this scenario. The first table is for a groundwater velocity of 21 m/yr. Sr-90 dominates at less than 0.001 rem/yr up to a dose time of 100 years. At 200 years and 20 meters, Am-241 delivers a dose rate of about 95 rem/yr. The Am-241 continues to dominate until about 5000 years, at that point it has decayed to lower levels and the Am-243 predominates. There are no areas contaminated above 0.5 rem/yr until 100 years after the shafts are sealed. The lower flow rate case results are in Table 6.68, the flow rate is 0.21 m/yr. The slow-moving aquifer delays the arrival of all contaminants until the 100-year dose time. Sr-90, Cs-135, and Sn-126 are the important nuclides before

Table 6.61

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
High Aquifer Velocity

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	4.42E-03 SN-126 91.9%	2.27E-04 CS-135 58.6%	1.61E-04 CS-135 58.6%	1.13E-04 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	4.45E-03 SN-126 91.9%	2.27E-04 CS-135 58.6%	1.61E-04 CS-135 58.6%	1.14E-04 CS-135 58.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	4.44E-03 SN-126 92.0%	2.81E-03 SN-126 92.0%	1.99E-03 SN-126 92.0%	1.13E-04 CS-135 58.7%	7.16E-05 CS-135 58.7%	5.85E-05 CS-135 58.7%	5.07E-05 CS-135 58.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	4.27E+02 AM-241 98.0%	2.79E-03 SN-126 92.0%	1.98E-03 SN-126 92.0%	1.40E-03 SN-126 92.0%	7.10E-05 CS-135 58.8%	5.80E-05 CS-135 58.8%	5.03E-05 CS-135 58.8%	4.12E-05 CS-135 58.8%	3.58E-05 CS-135 58.8%	0.0 NONE 0.0%
2.00E+02	3.64E+02 AM-241 97.7%	2.76E-03 SN-126 92.0%	1.96E-03 SN-126 92.0%	1.39E-03 SN-126 92.0%	6.98E-05 CS-135 59.1%	5.72E-05 CS-135 59.1%	4.96E-05 CS-135 59.1%	4.06E-05 CS-135 59.1%	3.52E-05 CS-135 59.1%	2.52E-05 CS-135 59.1%
5.00E+02	2.27E+02 AM-241 96.5%	1.46E+02 AM-241 96.5%	1.06E+02 AM-241 96.5%	1.34E-03 SN-126 92.1%	8.62E-04 SN-126 92.2%	7.11E-04 SN-126 92.3%	6.23E-04 SN-126 92.4%	3.88E-05 CS-135 60.0%	3.37E-05 CS-135 60.0%	2.41E-05 CS-135 60.0%
1.00E+03	1.05E+02 AM-241 93.1%	6.74E+01 AM-241 93.1%	4.89E+01 AM-241 93.1%	3.62E+01 AM-241 93.1%	8.15E-04 SN-126 92.4%	6.73E-04 SN-126 92.4%	5.90E-04 SN-126 92.5%	4.92E-04 SN-126 92.7%	4.36E-04 SN-126 92.8%	2.24E-05 CS-135 61.4%
2.00E+03	2.56E+01 AM-241 76.6%	1.64E+01 AM-241 76.6%	1.18E+01 AM-241 76.6%	8.78E+00 AM-241 76.6%	7.34E-04 SN-126 92.6%	6.01E-04 SN-126 92.6%	5.27E-04 SN-126 92.7%	4.41E-04 SN-126 92.8%	3.91E-04 SN-126 93.0%	3.02E-04 SN-126 93.6%
5.00E+03	3.50E+00 AM-243 95.4%	2.25E+00 AM-243 95.4%	1.63E+00 AM-243 95.5%	1.20E+00 AM-243 95.5%	8.82E-01 AM-243 95.5%	8.10E-01 AM-243 95.5%	7.93E-01 AM-243 95.5%	3.15E-04 SN-126 93.5%	2.79E-04 SN-126 93.6%	2.18E-04 SN-126 94.1%
1.00E+04	1.29E+00 AM-243 99.6%	8.33E-01 AM-243 99.6%	6.01E-01 AM-243 99.7%	4.43E-01 AM-243 99.7%	3.28E-01 AM-243 99.7%	2.98E-01 AM-243 99.8%	2.89E-01 AM-243 99.8%	3.04-01 AM-243 99.8%	3.33E-01 AM-243 99.9%	1.26E-04 SN-126 94.6%

Table 6.62

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Borehole Drilling in BEDDED SALT
1000 Years After Repository Sealing

Drill Hits Repository Water
Low Aquifer Velocity

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	3.58E-02 CS-135 58.8%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	3.52E-02 CS-135 59.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	3.37E-02 CS-135 60.0%	2.16E-02 CS-135 60.0%	1.57E-02 CS-135 60.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	4.36E-01 SN-126 92.8%	2.01E-02 CS-135 61.4%	1.46E-02 CS-135 61.4%	1.08E-02 CS-135 61.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+03	3.91E-01 SN-126 93.0%	1.75E-02 CS-135 64.1%	1.26E-02 CS-135 64.1%	9.36E-03 CS-135 64.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+03	2.79E-01 SN-126 93.6%	2.05E-01 SN-126 94.4%	1.81E-01 SN-126 95.4%	6.13E-03 CS-135 71.7%	4.54E-03 CS-135 71.7%	4.17E-03 CS-135 71.7%	4.05E-03 CS-135 71.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+04	3.33E+02 AM-243 99.9%	1.19E-01 SN-126 94.9%	1.04E-01 SN-126 95.8%	1.18E-01 SN-126 97.2%	2.41E-03 CS-135 81.7%	2.19E-03 CS-135 81.7%	2.13E-03 CS-135 81.7%	2.24E-03 CS-135 81.7%	2.45E-03 CS-135 81.7%	0.0 NONE 0.0%

Table 6.63

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Waste Directly Affected
High Aquifer Velocity

TIME (yr)	DISTANCE (meters)									
	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.74E+01 AM-241 95.7%	2.74E+01 AM-241 95.7%	2.74E+01 AM-241 95.7%	2.74E+01 AM-241 95.6%	2.74E+01 AM-241 95.6%	2.74E+01 AM-241 95.6%	2.74E+01 AM-241 95.6%	2.74E+01 AM-241 95.6%	2.74E+01 AM-241 95.6%	2.74E+01 AM-241 95.6%
2.00E+01	6.30E+01 AM-241 95.6%	6.30E+01 AM-241 95.6%	6.30E+01 AM-241 95.6%	6.30E+01 AM-241 95.6%	6.30E+01 AM-241 95.6%	6.30E+01 AM-241 95.6%	6.30E+01 AM-241 95.6%	6.30E+01 AM-241 95.6%	6.30E+01 AM-241 95.6%	6.30E+01 AM-241 95.6%
5.00E+01	1.28E+02 AM-241 95.4%	1.28E+02 AM-241 95.4%	1.28E+02 AM-241 95.4%	1.28E+02 AM-241 95.4%	1.28E+02 AM-241 95.4%	1.28E+02 AM-241 95.4%	1.28E+02 AM-241 95.4%	1.28E+02 AM-241 95.4%	1.28E+02 AM-241 95.4%	1.28E+02 AM-241 95.4%
1.00E+02	1.84E+02 AM-241 95.1%	1.89E+02 AM-241 95.1%	1.89E+02 AM-241 95.1%	1.89E+02 AM-241 95.1%	1.89E+02 AM-241 95.1%	1.89E+02 AM-241 95.1%	1.89E+02 AM-241 95.1%	1.89E+02 AM-241 95.1%	1.89E+02 AM-241 95.1%	1.89E+02 AM-241 95.1%
2.00E+02	1.58E+02 AM-241 94.4%	2.48E+02 AM-241 94.4%	2.48E+02 AM-241 94.4%	2.48E+02 AM-241 94.4%	2.48E+02 AM-241 94.4%	2.48E+02 AM-241 94.4%	2.48E+02 AM-241 94.4%	2.48E+02 AM-241 94.4%	2.48E+02 AM-241 94.4%	2.48E+02 AM-241 94.4%
5.00E+02	1.00E+02 AM-241 91.6%	1.74E+02 AM-241 91.6%	2.56E+02 AM-241 91.6%	2.63E+02 AM-241 91.6%	2.63E+02 AM-241 91.6%	2.63E+02 AM-241 91.6%	2.63E+02 AM-241 91.6%	2.63E+02 AM-241 91.6%	2.63E+02 AM-241 91.6%	2.63E+02 AM-241 91.6%
1.00E+03	4.86E+01 AM-241 84.2%	8.46E+01 AM-241 84.2%	1.24E+02 AM-241 84.2%	1.78E+02 AM-241 84.2%	1.83E+02 AM-241 84.2%	1.83E+02 AM-241 84.2%	1.83E+02 AM-241 84.2%	1.83E+02 AM-241 84.2%	1.83E+02 AM-241 84.2%	1.83E+02 AM-241 84.2%
2.00E+03	1.46E+01 AM-241 55.8%	2.54E+01 AM-241 55.8%	3.74E+01 AM-241 55.8%	5.36E+01 AM-241 55.8%	7.68E+01 AM-241 55.8%	7.68E+01 AM-241 55.8%	7.68E+01 AM-241 55.8%	7.68E+01 AM-241 55.8%	7.68E+01 AM-241 55.8%	7.68E+01 AM-241 55.8%
5.00E+03	3.91E+00 AM-243 36.0%	6.80E+00 AM-243 36.0%	1.00E+01 AM-243 36.0%	1.43E+01 AM-243 36.0%	2.22E+01 AM-243 36.0%	2.65E+01 AM-243 36.0%	2.96E+01 AM-243 36.0%	3.01E+01 AM-243 36.0%	3.01E+01 AM-243 35.9%	3.01E+01 AM-243 35.9%
1.00E+04	1.66E+00 PU-239 36.8%	2.88E+00 PU-239 36.8%	4.24E+00 PU-239 36.8%	6.07E+00 PU-239 36.8%	9.41E+00 PU-239 36.8%	1.12E+01 PU-239 36.8%	1.25E+01 PU-239 36.8%	1.44E+01 PU-239 36.8%	1.57E+01 PU-239 36.8%	1.59E+01 PU-239 36.8%

Table 6.64

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement
1000 Years After Repository Sealing

Waste Directly Affected
Low Aquifer Velocity

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.16E-03 CS-135 53.3%	2.16E-03 CS-135 53.3%	2.16E-03 CS-135 53.3%	2.16E-03 CS-135 53.3%	2.16E-03 CS-135 53.3%	2.16E-03 CS-135 53.3%	2.16E-03 CS-135 53.3%	2.16E-03 CS-135 53.3%	2.16E-03 CS-135 53.3%	2.16E-03 CS-135 53.3%
2.00E+01	5.04E-03 CS-135 53.3%	5.04E-03 CS-135 53.3%	5.04E-03 CS-135 53.3%	5.04E-03 CS-135 53.3%	5.04E-03 CS-135 53.3%	5.04E-03 CS-135 53.3%	5.04E-03 CS-135 53.3%	5.04E-03 CS-135 53.3%	5.04E-03 CS-135 53.3%	5.04E-03 CS-135 53.3%
5.00E+01	1.19E-02 CS-135 47.9%	1.19E-02 CS-135 47.9%	1.19E-02 CS-135 47.9%	1.19E-02 CS-135 47.9%	1.19E-02 CS-135 47.9%	1.19E-02 CS-135 47.9%	1.19E-02 CS-135 47.9%	1.19E-02 CS-135 47.9%	1.19E-02 CS-135 47.9%	1.19E-02 CS-135 47.9%
1.00E+02	3.85E-02 SN-126 57.2%	3.90E-02 SN-126 56.5%	3.90E-02 SN-126 56.5%	3.90E-02 SN-126 56.5%	3.90E-02 SN-126 56.5%	3.90E-02 SN-126 56.5%	3.90E-02 SN-126 56.5%	3.90E-02 SN-126 56.5%	3.90E-02 SN-126 56.5%	3.90E-02 SN-126 56.5%
2.00E+02	6.69E-02 SN-126 75.7%	7.63E-02 SN-126 66.5%	7.63E-02 SN-126 66.5%	7.63E-02 SN-126 66.5%	7.63E-02 SN-126 66.5%	7.63E-02 SN-126 66.5%	7.63E-02 SN-126 66.5%	7.63E-02 SN-126 66.5%	7.63E-02 SN-126 66.5%	7.63E-02 SN-126 66.5%
5.00E+02	6.48E+01 AM-241 96.2%	6.48E+01 AM-241 96.2%	6.48E+01 AM-241 96.2%	6.48E+01 AM-241 96.2%	6.48E+01 AM-241 96.2%	6.48E+01 AM-241 96.2%	6.48E+01 AM-241 96.2%	6.48E+01 AM-241 96.2%	6.48E+01 AM-241 96.2%	6.48E+01 AM-241 96.2%
1.00E+03	5.32E+02 AM-241 92.8%	5.32E+02 AM-241 92.8%	5.33E+02 AM-241 92.8%	5.33E+02 AM-241 92.8%	5.33E+02 AM-241 92.8%	5.33E+02 AM-241 92.8%	5.33E+02 AM-241 92.8%	5.33E+02 AM-241 92.8%	5.33E+02 AM-241 92.8%	5.33E+02 AM-241 92.8%
2.00E+03	2.92E+02 AM-241 75.6%	2.92E+02 AM-241 75.5%	2.92E+02 AM-241 75.5%	2.92E+02 AM-241 75.5%	2.92E+02 AM-241 75.5%	2.92E+02 AM-241 75.5%	2.92E+02 AM-241 75.5%	2.92E+02 AM-241 75.5%	2.92E+02 AM-241 75.5%	2.92E+02 AM-241 75.5%
5.00E+03	8.37E+01 AM-243 86.8%	8.38E+01 AM-243 86.7%	8.38E+01 AM-243 86.6%	8.38E+01 AM-243 86.6%	8.39E+01 AM-243 86.6%	8.39E+01 AM-243 86.6%	8.39E+01 AM-243 86.6%	8.39E+01 AM-243 86.6%	8.39E+01 AM-243 86.6%	8.39E+01 AM-243 86.6%
1.00E+04	4.82E+01 AM-243 77.9%	4.91E+01 AM-243 77.7%	4.91E+01 AM-243 77.7%	4.92E+01 AM-243 77.6%	4.92E+01 AM-243 77.6%	4.92E+01 AM-243 77.6%	4.92E+01 AM-243 77.6%	4.92E+01 AM-243 77.6%	4.92E+01 AM-243 77.6%	4.92E+01 AM-243 77.6%

Table 6.65

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement in GRANITE
1000 Years After Repository Sealing

Repository Water Affected
High Aquifer Velocity

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	3.55E+05 AM-241 95.7%	3.55E+05 AM-241 95.7%	3.55E+05 AM-241 95.7%	3.55E+05 AM-241 95.7%	3.55E+05 AM-241 95.7%	3.55E+05 AM-241 95.7%	3.55E+05 AM-241 95.7%	3.55E+05 AM-241 95.7%	3.55E+05 AM-241 95.7%	3.55E+05 AM-241 95.7%
2.00E+01	2.50E+05 AM-241 95.6%	2.50E+05 AM-241 95.6%	2.50E+05 AM-241 95.6%	2.50E+05 AM-241 95.6%	2.50E+05 AM-241 95.6%	2.50E+05 AM-241 95.6%	2.50E+05 AM-241 95.6%	2.50E+05 AM-241 95.6%	2.50E+05 AM-241 95.6%	2.50E+05 AM-241 95.6%
5.00E+01	1.64E+05 AM-241 95.4%	1.64E+05 AM-241 95.4%	1.64E+05 AM-241 95.4%	1.64E+05 AM-241 95.4%	1.64E+05 AM-241 95.4%	1.64E+05 AM-241 95.4%	1.64E+05 AM-241 95.4%	1.64E+05 AM-241 95.4%	1.64E+05 AM-241 95.4%	1.64E+05 AM-241 95.4%
1.00E+02	2.78E+04 AM-241 95.1%	1.24E+05 AM-241 95.1%	1.24E+05 AM-241 95.1%	1.24E+05 AM-241 95.1%	1.24E+05 AM-241 95.1%	1.24E+05 AM-241 95.1%	1.24E+05 AM-241 95.1%	1.24E+05 AM-241 95.1%	1.24E+05 AM-241 95.1%	1.24E+05 AM-241 95.1%
2.00E+02	2.39E+04 AM-241 94.4%	9.60E+04 AM-241 94.4%	9.60E+04 AM-241 94.4%	9.60E+04 AM-241 94.4%	9.60E+04 AM-241 94.4%	9.60E+04 AM-241 94.4%	9.60E+04 AM-241 94.4%	9.60E+04 AM-241 94.4%	9.60E+04 AM-241 94.4%	9.60E+04 AM-241 94.4%
5.00E+02	1.52E+04 AM-241 91.6%	2.67E+04 AM-241 91.6%	3.99E+04 AM-241 91.6%	6.47E+04 AM-241 91.6%	6.47E+04 AM-241 91.6%	6.47E+04 AM-241 91.6%	6.47E+04 AM-241 91.6%	6.47E+04 AM-241 91.6%	6.47E+04 AM-241 91.6%	6.47E+04 AM-241 91.6%
1.00E+03	7.36E+03 AM-241 84.2%	1.30E+04 AM-241 84.2%	1.94E+04 AM-241 84.2%	2.87E+04 AM-241 84.2%	3.79E+04 AM-241 84.2%	3.79E+04 AM-241 84.2%	3.79E+04 AM-241 84.2%	3.79E+04 AM-241 84.2%	3.79E+04 AM-241 84.2%	3.79E+04 AM-241 84.2%
2.00E+03	2.22E+03 AM-241 55.8%	3.91E+03 AM-241 55.8%	5.83E+03 AM-241 55.8%	8.64E+03 AM-241 55.8%	1.50E+04 AM-241 55.8%	1.50E+04 AM-241 55.8%	1.50E+04 AM-241 55.8%	1.50E+04 AM-241 55.8%	1.50E+04 AM-241 55.8%	1.50E+04 AM-241 55.8%
5.00E+03	5.94E+02 AM-243 36.1%	1.04E+03 AM-243 36.0%	1.56E+03 AM-243 36.0%	2.32E+03 AM-243 36.0%	3.97E+03 AM-243 36.0%	5.12E+03 AM-243 36.0%	6.20E+03 AM-243 36.0%	6.73E+03 AM-243 36.0%	6.73E+03 AM-243 36.0%	6.73E+03 AM-243 36.0%
1.00E+04	2.53E+02 PU-239 36.7%	4.44E+02 PU-239 36.7%	6.64E+02 PU-239 36.7%	9.84E+02 PU-239 36.7%	1.68E+03 PU-239 36.6%	2.17E+03 PU-239 36.7%	2.64E+03 PU-239 36.7%	3.56E+03 PU-239 36.7%	4.56E+03 PU-239 36.7%	4.89E+03 PU-239 36.7%

Table 6.66

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Fault Movement in GRANITE
1000 Years After Repository Sealing

Repository Water Affected
Low Aquifer Velocity

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	5.71E+00 TC -99 52.2%	5.71E+00 TC -99 52.2%	5.71E+00 TC -99 52.2%	5.71E+00 TC -99 52.2%	5.71E+00 TC -99 52.2%	5.71E+00 TC -99 52.2%	5.71E+00 TC -99 52.2%	5.71E+00 TC -99 52.2%	5.71E+00 TC -99 52.2%	5.71E+00 TC -99 52.2%
2.00E+01	1.22E+01 TC -99 52.2%	1.22E+01 TC -99 52.2%	1.22E+01 TC -99 52.2%	1.22E+01 TC -99 52.2%	1.22E+01 TC -99 52.2%	1.22E+01 TC -99 52.2%	1.22E+01 TC -99 52.2%	1.22E+01 TC -99 52.2%	1.22E+01 TC -99 52.2%	1.22E+01 TC -99 52.2%
5.00E+01	2.15E+01 TC -99 48.0%	2.15E+01 TC -99 48.0%	2.15E+01 TC -99 48.0%	2.15E+01 TC -99 48.0%	2.15E+01 TC -99 48.0%	2.15E+01 TC -99 48.0%	2.15E+01 TC -99 48.0%	2.15E+01 TC -99 48.0%	2.15E+01 TC -99 48.0%	2.15E+01 TC -99 48.0%
1.00E+02	4.14E+01 SN-126 51.6%	4.28E+01 SN-126 49.9%	4.28E+01 SN-126 49.9%	4.28E+01 SN-126 49.9%	4.28E+01 SN-126 49.9%	4.28E+01 SN-126 49.9%	4.28E+01 SN-126 49.9%	4.28E+01 SN-126 49.9%	4.28E+01 SN-126 49.9%	4.28E+01 SN-126 49.9%
2.00E+02	3.42E+01 SN-126 79.5%	4.68E+01 SN-126 58.1%	4.68E+01 SN-126 58.1%	4.68E+01 SN-126 58.1%	4.68E+01 SN-126 58.1%	4.68E+01 SN-126 58.1%	4.68E+01 SN-126 58.1%	4.68E+01 SN-126 58.1%	4.68E+01 SN-126 58.1%	4.68E+01 SN-126 58.1%
5.00E+02	9.02E+04 AM-241 91.6%	9.02E+04 AM-241 91.6%	9.02E+04 AM-241 91.6%	9.02E+04 AM-241 91.6%	9.02E+04 AM-241 91.6%	9.02E+04 AM-241 91.6%	9.02E+04 AM-241 91.6%	9.02E+04 AM-241 91.6%	9.02E+04 AM-241 91.6%	9.02E+04 AM-241 91.6%
1.00E+03	1.82E+05 AM-241 84.2%	1.82E+05 AM-241 84.2%	1.82E+05 AM-241 84.1%	1.82E+05 AM-241 84.1%	1.82E+05 AM-241 84.1%	1.82E+05 AM-241 84.1%	1.82E+05 AM-241 84.1%	1.82E+05 AM-241 84.1%	1.82E+05 AM-241 84.1%	1.82E+05 AM-241 84.1%
2.00E+03	9.37E+04 AM-241 55.8%	9.37E+04 AM-241 55.8%	9.37E+04 AM-241 55.8%	9.37E+04 AM-241 55.8%	9.37E+04 AM-241 55.8%	9.37E+04 AM-241 55.8%	9.37E+04 AM-241 55.8%	9.37E+04 AM-241 55.8%	9.37E+04 AM-241 55.8%	9.37E+04 AM-241 55.8%
5.00E+03	5.29E+04 AM-243 36.0%	5.29E+04 AM-243 35.9%	5.29E+04 AM-243 35.9%	5.29E+04 AM-243 35.9%	5.29E+04 AM-243 35.9%	5.30E+04 AM-243 35.9%	5.30E+04 AM-243 35.9%	5.30E+04 AM-243 35.9%	5.30E+04 AM-243 35.9%	5.30E+04 AM-243 35.9%
1.00E+04	3.90E+04 PU-239 36.8%	4.32E+04 PU-239 36.8%	4.32E+04 PU-239 36.8%	4.32E+04 PU-239 36.8%	4.32E+04 PU-239 36.7%	4.32E+04 PU-239 36.7%	4.32E+04 PU-239 36.7%	4.32E+04 PU-239 36.7%	4.32E+04 PU-239 36.7%	4.32E+04 PU-239 36.7%

Table 6.67

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Shaft Seal Leakage in GRANITE

High Aquifer Velocity

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	2.86E-05 SR -90 68.8%	1.40E-05 SR -90 69.4%	5.91E-06 SR -90 69.3%	2.66E-07 SR -90 68.4%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	8.15E-05 SR -90 60.6%	4.00E-05 SR -90 68.7%	2.24E-05 SR -90 68.7%	8.87E-06 SR -90 68.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	2.75E-04 SR -90 44.4%	1.38E-04 SR -90 53.2%	7.22E-05 SR -90 65.5%	4.16E-05 SR -90 66.0%	1.24E-05 SR -90 66.0%	3.73E-06 SR -90 66.0%	2.79E-07 SR -90 65.6%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	7.02E-01 AM-241 98.9%	3.19E-04 SN-126 55.6%	1.59E-04 SN-126 40.0%	6.26E-05 SR -90 56.2%	2.85E-05 SR -90 57.1%	1.71E-05 SR -90 57.1%	1.02E-05 SR -90 57.1%	2.88E-06 SR -90 57.1%	1.64E-07 SR -90 56.5%	0.0 NONE 0.0%
2.00E+02	9.47E+01 AM-241 98.8%	9.43E-04 SN-126 86.4%	5.32E-04 SN-126 83.3%	2.18E-04 SN-126 72.5%	3.30E-05 CS-135 40.2%	2.37E-05 CS-135 40.2%	1.79E-05 CS-135 40.2%	1.08E-05 CS-135 40.1%	6.41E-06 CS-135 40.1%	7.76E-08 CS-135 39.3%
5.00E+02	6.68E+02 AM-241 98.3%	2.00E+02 AM-241 98.3%	1.94E+00 AM-241 98.1%	1.96E-03 SN-126 89.2%	6.49E-04 SN-126 80.4%	2.43E-04 SN-126 59.1%	8.77E-05 CS-135 55.2%	6.16E-05 CS-135 58.6%	4.85E-05 CS-135 58.6%	2.17E-05 CS-135 58.6%
1.00E+03	1.14E+03 AM-241 96.5%	5.57E+02 AM-241 96.5%	2.19E+02 AM-241 96.5%	2.20E+00 AM-241 96.2%	3.41E-03 SN-126 89.0%	2.21E-03 SN-126 86.3%	1.45E-03 SN-126 82.3%	5.52E-04 SN-126 63.4%	1.80E-04 CS-135 56.1%	1.01E-04 CS-135 60.1%
2.00E+03	7.48E+02 AM-241 87.0%	4.31E+02 AM-241 87.0%	2.54E+02 AM-241 87.0%	1.09E+02 AM-241 86.9%	1.05E-02 SN-126 91.3%	7.88E-03 SN-126 90.7%	6.26E-03 SN-126 89.9%	4.19E-03 SN-126 87.9%	2.84E-03 SN-126 84.7%	3.18E-04 CS-135 57.0%
5.00E+03	1.74E+02 AM-243 91.4%	1.09E+02 AM-243 91.4%	7.60E+01 AM-243 91.4%	5.11E+01 AM-243 91.4%	2.30E+01 AM-243 91.4%	8.90E+00 AM-243 95.3%	4.57E-01 AM-243 95.7%	1.31E-02 SN-126 92.7%	1.10E-02 SN-126 92.5%	6.56E-03 SN-126 91.1%
1.00E+04	7.03E+01 AM-243 99.9%	4.54E+01 AM-243 99.9%	3.32E+01 AM-243 99.9%	2.51E+01 AM-243 99.9%	1.86E+01 AM-243 99.9%	1.65E+01 AM-243 99.9%	1.45E+01 AM-243 99.9%	8.39E+00 AM-243 99.9%	6.55E-01 AM-243 98.6%	6.95E-03 SN-126 94.9%

Table 6.68

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Radionuclides
Released by Shaft Seal Leakage in GRANITE

Low Aquifer Velocity

	DISTANCE (meters)									
TIME (yr)	20.00	50.00	100.00	200.00	500.00	750.00	1000.00	1500.00	2000.00	4000.00
1.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+01	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+02	1.64E-04 SR -90 56.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+02	6.41E-03 CS-135 40.1%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+02	4.85E-02 CS-135 58.6%	1.45E-02 CS-135 58.6%	1.43E-04 CS-135 57.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+03	1.80E-01 CS-135 56.1%	8.25E-02 CS-135 60.1%	3.24E-02 CS-135 60.0%	3.27E-04 CS-135 59.7%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
2.00E+03	2.84E+00 SN-126 84.7%	2.50E-01 CS-135 62.9%	1.47E-01 CS-135 62.9%	6.28E-02 CS-135 62.9%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
5.00E+03	1.10E+01 SN-126 92.5%	5.11E+00 SN-126 89.9%	4.56E-01 CS-135 55.8%	2.42E-01 CS-135 70.6%	1.09E-01 CS-135 70.6%	4.40E-02 CS-135 70.6%	2.27E-03 CS-135 70.5%	0.0 NONE 0.0%	0.0 NONE 0.0%	0.0 NONE 0.0%
1.00E+04	6.55E+02 AM-243 98.6%	6.50E+00 SN-126 95.0%	5.05E+00 SN-126 95.3%	3.92E-01 SN-126 54.6%	1.32E-01 CS-135 81.0%	1.17E-01 CS-135 81.0%	1.03E-01 CS-135 81.0%	5.95E-02 CS-135 81.0%	4.59E-03 CS-135 81.0%	0.0 NONE 0.0%

Table 6.69

Area (ha*) of the Aquifer Contaminated
Above the Specified Dose Rate Levels
Following Drilling 1000 Years after Sealing

Variable aquifer velocity

Event description/ aquifer velocity	Length of time after event (yr)	Dose Rate Levels (rem/yr)			
		0.5	5	50	500
Direct hit on waste/v = 21 m/yr	0-50	0	0	0	0
	100	0.21	0.18	0.13	0.05
	200	0.21	0.17	0.13	0.04
	500	0.99	0.78	0.49	0
	1000	2.85	2.09	0.75	0
	2000	2.41	1.43	0	0
	5000	9.46	0.03	0	0
	10000	10.2	0	0	0
v = 0.21 m/yr	0-5000	0	0	0	0
	10000	0.30	0.24	0.14	0
Drill hits granite tank/v = 21 m/yr	0-50	0	0	0	0
	100	0.23	0.19	0.15	0.09
	200	0.23	0.19	0.15	0.09
	500	1.08	0.89	0.65	0.20
	1000	3.17	2.51	1.60	0.90
	2000	2.93	2.19	1.01	0
	5000	14.7	4.39	0	0
	10000	42.0	0.05	0	0
v = 0.21 m/yr	0-500	0	0	0	0
	1000	0.08	0	0	0
	2000	0.11	0	0	0
	5000	0.27	0	0	0
	10000	0.34	0.28	0.21	0.08
Drill hits brine pocket/v = 21 m/yr	0-50	0	0	0	0
	100	0.22	0.19	0.14	0.08
	200	0.22	0.19	0.14	0.07
	500	1.04	0.84	0.58	0.05
	1000	3.02	2.31	1.26	0
	2000	2.61	1.74	0.07	0
	5000	11.8	0.16	0	0
	10000	27.4	0	0	0

v = 0.21 m/yr	0-5000	0	0	0	0
	10000	0.32	0.25	0.17	0
Shaft seal release/v = 21 m/yr	0-50	0	0	0	0
	100	0.23	0.19	0.15	0.08
	200	0.22	0.19	0.14	0.08
	500	1.05	0.85	0.60	0.08
	1000	3.05	2.36	1.34	0
	2000	2.63	1.77	0.86	0
	5000	11.0	0.10	0	0
	10000	23.7	0	0	0
v = 0.21 m/yr	0-5000	0	0	0	0
	10000	0.31	0.25	0.16	0

10,000 years, when Am-243 appears. The maximum dose rate is 650 rem/yr at the 10,000-year, 20-meter point. No areas are contaminated until 10,000 years, and even then they are very small (Table 6.69).

6.7 Summary

Two characteristics of the repository system have the greatest effect on potential individual dose from high-level and transuranic radioactive wastes after disposal in a geologic repository. These two parameters are the solubility of radionuclides in the water in that repository and the retardation factors for nuclides in the groundwater (aquifer) strata. If the geochemistry is such that nuclides dissolve in the repository water and are leach-limited rather than solubility-limited, the isotopes of technetium, neptunium, and, especially, plutonium become available in much greater quantities. The highest dose rates are not much affected, but the duration of contamination is much longer because nuclides of these three elements, especially plutonium, persist after other nuclides, such as the americium isotopes, have been reduced by decay.

If the nuclides are not sorbed on the rock materials of the groundwater strata, they will move along with the groundwater (retardation factor of one). Early doses rates will be much larger than they would be if the nuclides were retarded and the extent of contamination will be much greater. The highest dose rates will be somewhat higher than they would be with retardation because more nuclides will reach a given point together. On the other hand, if nuclides are sorbed on groundwater strata to a greater degree than in the base case, they will move so slowly that a great many of them will decay to very low levels before they have moved more than a few meters. Doses at all points and times will be much lower than they are in the base case and only very small portions of the groundwater will be contaminated.

Changing the leach rate of nuclides affects the dose rates in two ways. Early dose rates are much higher with higher leach rates, but the persistence of these doses is less because the waste in the repository is rapidly depleted by the rapid leaching.

Changing the groundwater velocity effects the time it takes a nuclide to reach a given point and the diffusion rates of the nuclides in the aquifer. Larger velocities have the same effect as small retardation factors (Note the kx/v term in all equations).

Changing the high, constant permeability to a linear, degrading permeability generally results in smaller doses due to a lower flow rate. The lower flow rate restricts the entry of solubility-limited nuclides into the aquifer. In one case, the salt brine pocket, the dose rates are higher. The tank is small and the low flow rate allows the Am-241 to reach its solubility limit. The product of the solubility and the flow rate is about 2.4 times that of the base case.

Changing the canister life to 1000 years causes all base case tank releases to be zero. The direct hit cases are changed only slightly in the leaching time a canister undergoes. A canister life of 0 years, instant failure, causes all nuclides to begin leaching or dissolving immediately after they are buried. The canister life has the smallest effect of all parameters varied.

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