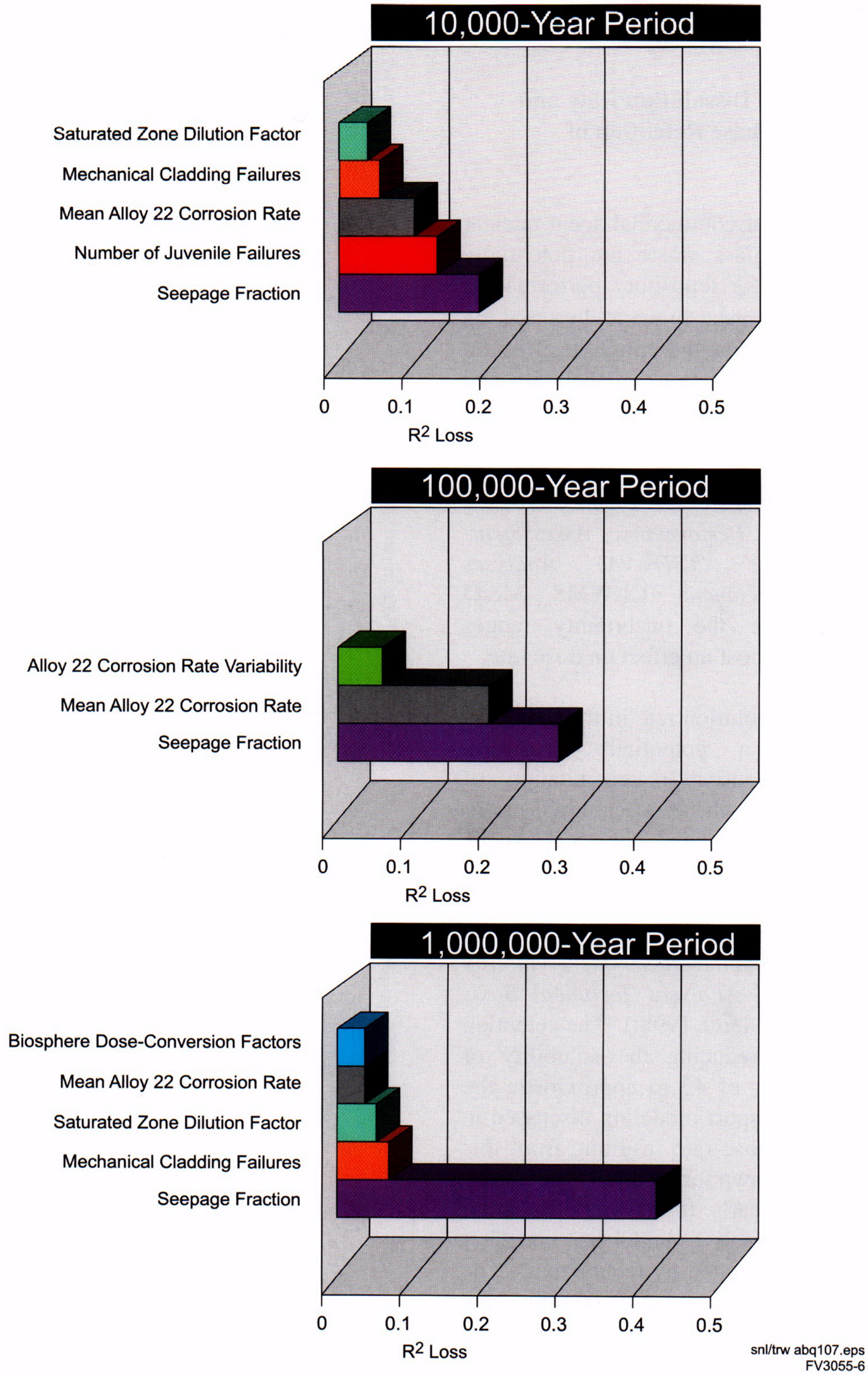

Figure 5-31. Most Important Parameters for the Modified Cladding Model Case
Results are from stepwise regression analysis for three time periods. These charts show the relative importance of various parameters to the calculated uncertainty in dose rate for the three time periods. Importance of an individual parameter is shown by R^2-loss, the reduction of goodness of the regression fit.

prevents the cladding from having much of an effect.

5.5.3 Sensitivity to Dissolution Rate and Secondary-Phase Retention of Neptunium

The dissolution rates of commercial spent nuclear fuel and high-level glass waste are potentially important parameters for repository performance, although they did not appear in the R^2-loss ranking in Figure 4-34. To examine their possible effect on dose rate, the single realizations of their 5th and 95th percentile values are compared to the expected-value base case in Figure 5-32. The uncertainty ranges in these parameters are derived from experimental studies described in Chapter 6 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i). Clearly for the uncertainty ranges considered, there is almost no effect on dose rate.

The uncertainty in dissolution rate in the base case did not consider a potentially important phenomenon: the retention (re-precipitation) of neptunium in secondary phases after initial dissolution. This effect is observed in laboratory experiments (Finn et al. 1997) The effect of such retention is analyzed as an alternative model described in Section 3.5 and in Chapter 6 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i). The retention effect is gained by reducing the solubility of neptunium by a factor of 45 to approximate the results of reactive transport modeling discussed in Section 3.5.2.5. The dose rate resulting from this alternative model is shown for all three time frames in Figure 5-33. At early times, prior to about 50,000 years, the alternative model has no effect because doses are dominated by technetium. The greatest effect is noticed at about 200,000 years when neptunium comprises more than 99 percent of the total dose in the base case (see Figure 4-12). At this time, the total dose from the alternative neptunium solubility model is about a factor of 25 lower than the base case total dose rate. If the total dose rate at this time in the alternative model were

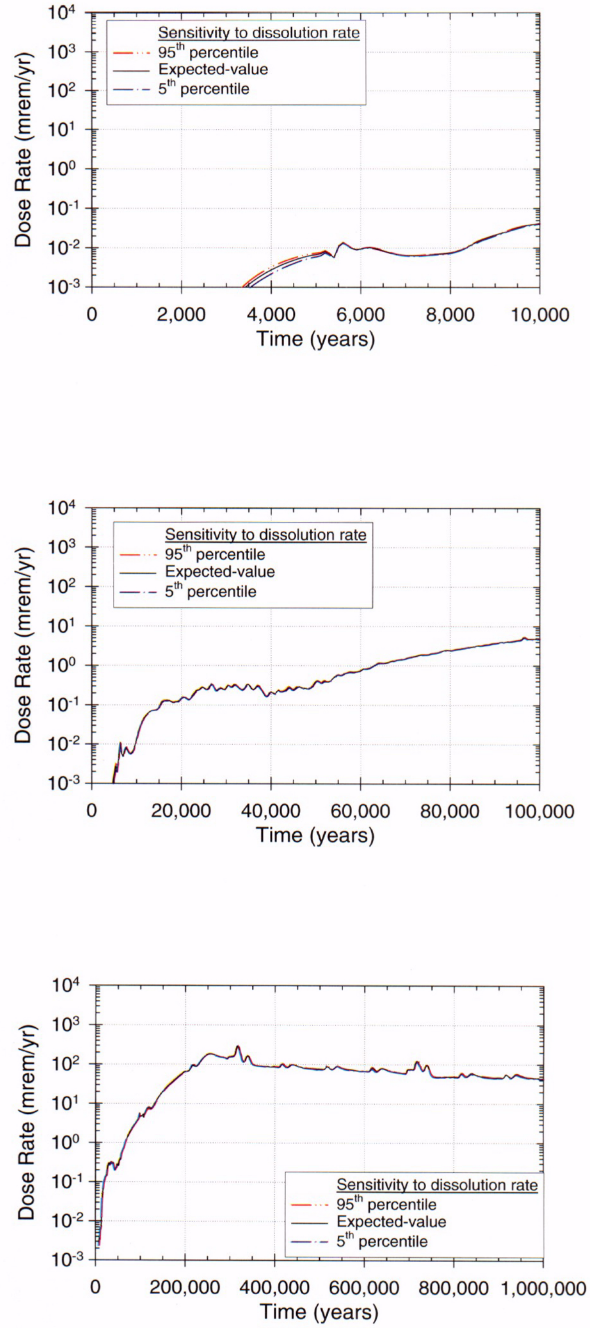

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Figure 5-32. Effect of Commercial-Spent-Fuel and High-Level-Glass Dissolution Rates on Total Dose Rate
Comparison of base case expected-value dissolution rates with the base case 5th and 95th percentile values.

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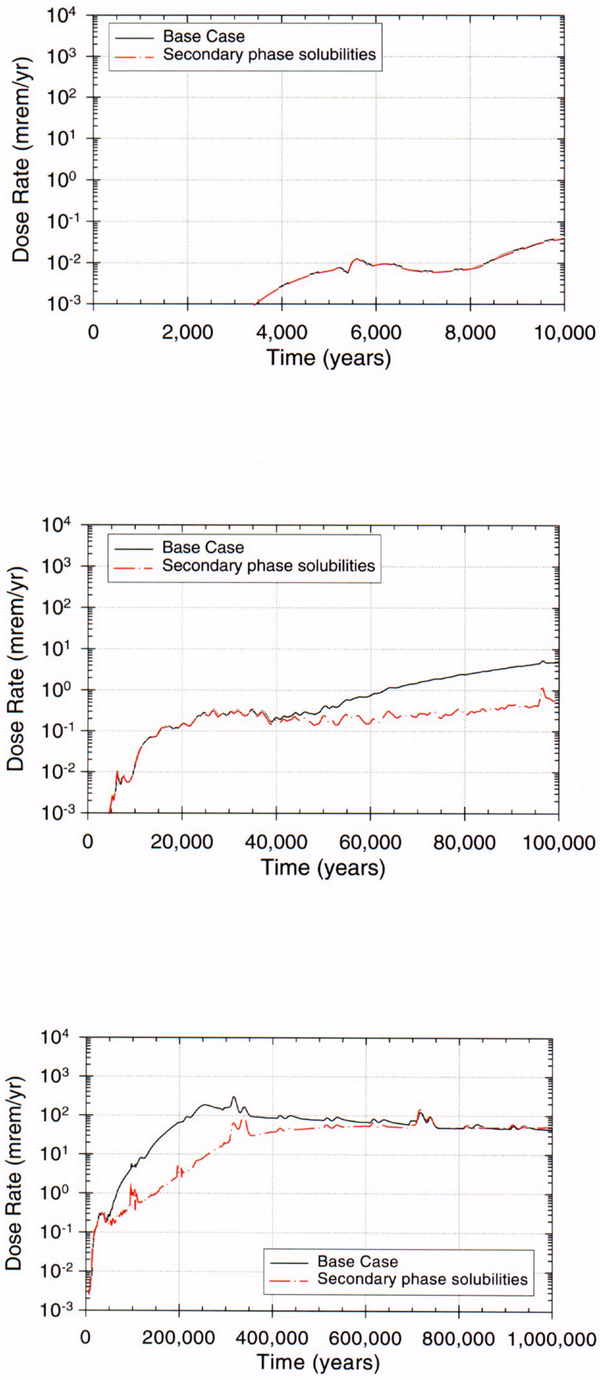

Figure 5-33. Sensitivity of Total Dose Rate to Reprecipitation of Neptunium in Secondary Mineral Phases
These phases have lower solubility than the primary mineral phases. This effect is implemented by dividing the base case neptunium solubility by 45.

composed almost solely of neptunium, as it is in the base case, then the difference between the two models would be exactly a factor of 45 because of the difference in neptunium solubility. However, in the alternative model the neptunium dose is low enough at this time that some of the other radionuclides, such as plutonium-242, uranium-234, and technetium-99 (see Figure 4-12) have a non-negligible contribution to dose. At a later times (> 250,000 years), the effect of the alternative neptunium model is not as significant because neptunium is no longer solubility limited (all waste packages have failed) and the cladding degradation rate limits the surface area available for dissolution and release.

The retention of neptunium as a secondary phase, while a potentially important effect in repository performance, is still being evaluated in laboratory testing and corresponding reactive transport modeling. Further analyses are necessary before including such effects in the base case TSPA.

5.5.4 Sensitivity of Dose to Neptunium Solubility

The solubility of neptunium is uncertain to within at least a three-order of magnitude range as shown by the shaded region in Figure 5-34. This shaded region was the range of neptunium solubility used in the TSPA-VA base case. It does not encompass all experimental measurements, as shown in the figure, but the measurements outside of this range are thought to be unrepresentative of any potential repository conditions, as described briefly in Section 3.5.1.8 and in much more detail in Chapter 6 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i). Neptunium solubility did not appear as one of the most important rank-regression parameters in Figure 4-34, however, it did appear as an important parameter in Figure 4-40 for the 100,000-year time span, when the seepage and corrosion-rate parameters were held at their mean values. In other words it was in the second-tier of key R^2-loss parameters. However, it only appears in the second tier during the 100,000-year time frame because this is the time frame when

C-91

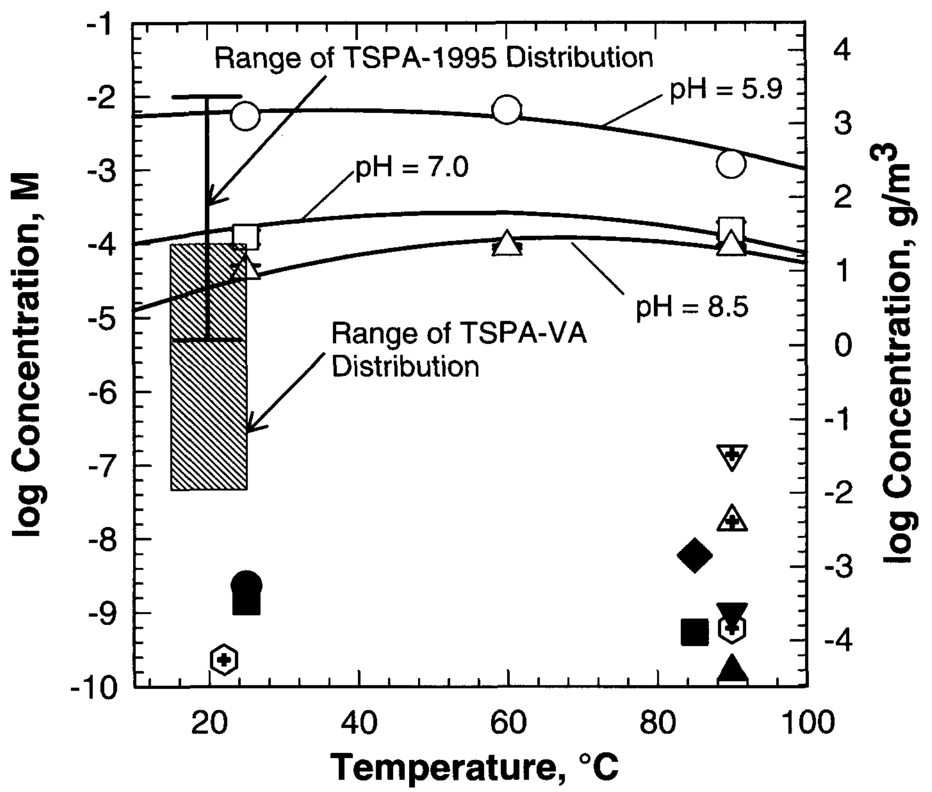

Figure 5-34. TSPA-VA Base Case Neptunium Solubility Distribution Compared to TSPA-1995 Distribution and to Eleven Different Precipitation/Dissolution Experiments
The open symbols at the top of the diagram are precipitation (oversaturation) experiments. The filled symbols at the bottom are dissolution studies, including batch, flow-through, and drip experiments. See Chapter 6 of CRWMS M&O 1998i for more detail.

solubility-limited neptunium tends to dominate doses. This is born out in the total-dose time-history comparison shown in Figure 5-35, comparing the expected-value neptunium solubility case to the dose rate arising from the 5th and 95th percentile values from the base case neptunium solubility range.[2] As with the secondary-phase model described by Figure 5-33, the greatest effect on dose for the base case model is in the time frame of 50,000 to 250,000 years when the total dose is dominated by solubility-limited neptunium releases. At later times the cladding degradation rate controls total dose rate.

5.5.5 Sensitivity to Formation and Transport of Radionuclide-Bearing Colloids

Uncertainty in colloid formation and transport parameters is quite high in the TSPA-VA base case (see Tables 3-16 and 3-18), particularly in far-field transport, because of a lack of experimental or field-scale evidence to verify the models. Nevertheless, for the models and parameters used in the base case, colloid model parameters do not show up in the key rank-regression parameters in Figures 4-34 or 4-40, even though Figure 4-29 indicates that plutonium dose rate is the most significant contributor to total dose rate for 2 percent of the 100,000-year multiple realizations

[2] Neptunium solubility was modeled as a log-beta distribution and the 5th, 95th, and expected values were chosen for the log of solubility, not for the solubility itself.

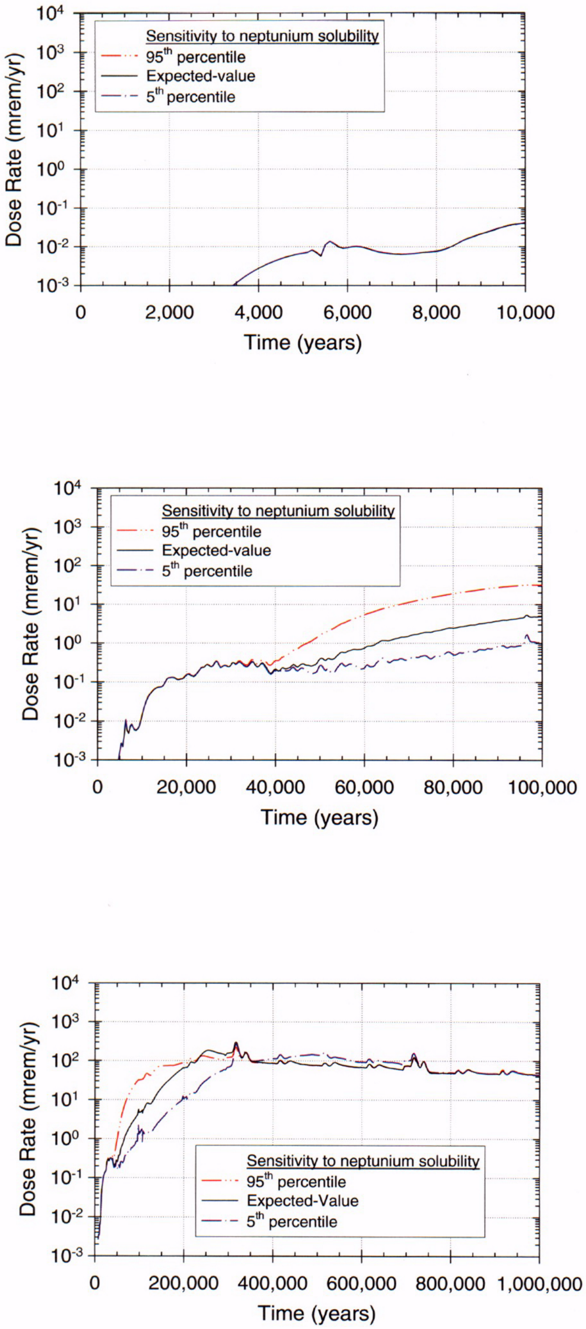

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Figure 5-35. Effect of Neptunium Solubility on Total Dose Rate
Comparison of base case expected-value solubility with the base case 5th and 95th percentile values.

and 8 percent of the 1-million-year multiple realizations. However, in examining the sensitivity to the 95th percentile value of the K_c range ($K_c = 5.0$) in the base case, it is evident that there is an effect on dose rate during the 50,000-year to 250,000-year time period, as indicated in Figure 5-36. The K_c parameter is high enough at this percentile to allow a significant fraction of plutonium to be transported as reversibly sorbing on colloids. There is no difference in this figure between the 5th percentile value for K_c and the expected-value because the expected value is already too low to allow a significant fraction of aqueous plutonium to be transported in colloidal form.

5.5.6 Sensitivity to Transport in the Engineered Barrier System

The TSPA-VA base case evaluation includes radionuclide retardation in the concrete invert (i.e., the structure that supports the waste package) for neptunium, plutonium, uranium, and protactinium. There is uncertainty in the appropriate values for these retardation factors (as indicated by the ranges given in Section 4.1.10) and about what will happen to the retardation capability of the invert over a long time as the system degrades. To evaluate the effect on dose rate of the retardation capability of the invert, a sensitivity case was conducted (Figure 5-37) using the 5th and 95th percentiles of these K_d ranges. The results indicate that for early times (< 35,000 years) when the dose is dominated by technetium release (no retardation), there is no change. At later times when the dose is primarily a result of neptunium release, the difference in total dose rate mimics the change in neptunium dose rate, but the increase is less than a factor of two. At much later times (> 250,000 years) cladding degradation rate eliminates any difference between the cases.

An additional sensitivity analysis was carried out to examine retardation in the invert. This is an alternative model wherein all the distribution coefficients (K_ds) in the invert are set to zero (i.e., no retardation in the invert). Figure 5-38 presents the results of these analyses, which are about the same as the 5th percentile case in Figure 5-37. In

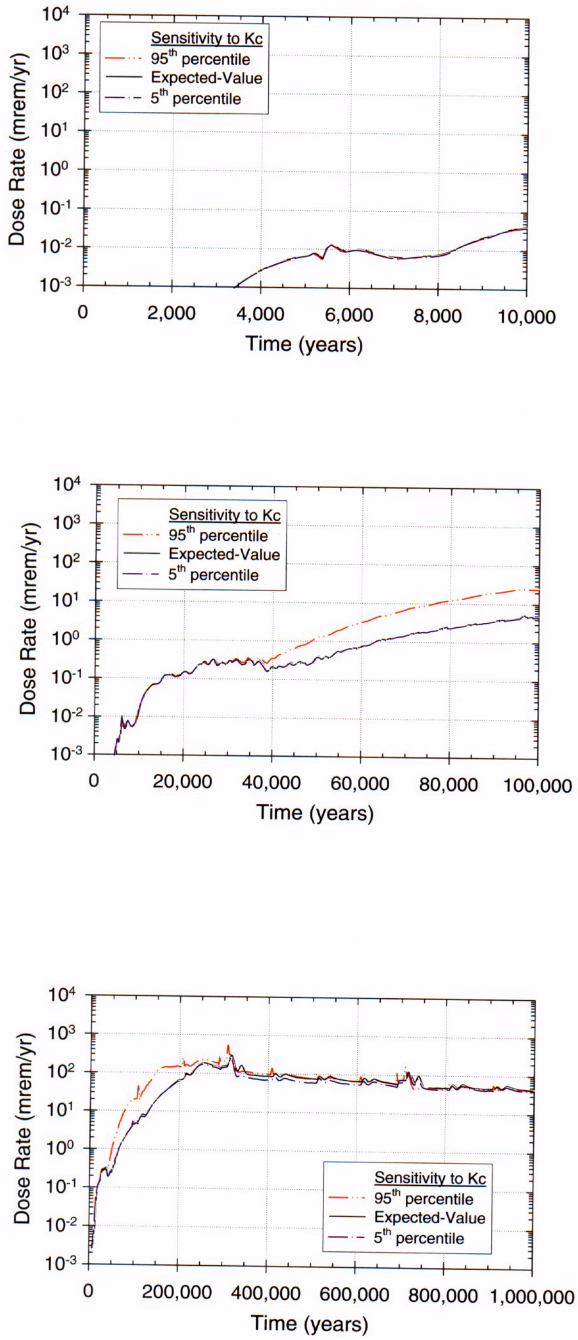

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Figure 5-36. Effect of Colloid Distribution Coefficient on Total Dose Rate
Comparison of base case expected-value K_c with the base case 5th and 95th percentile values.

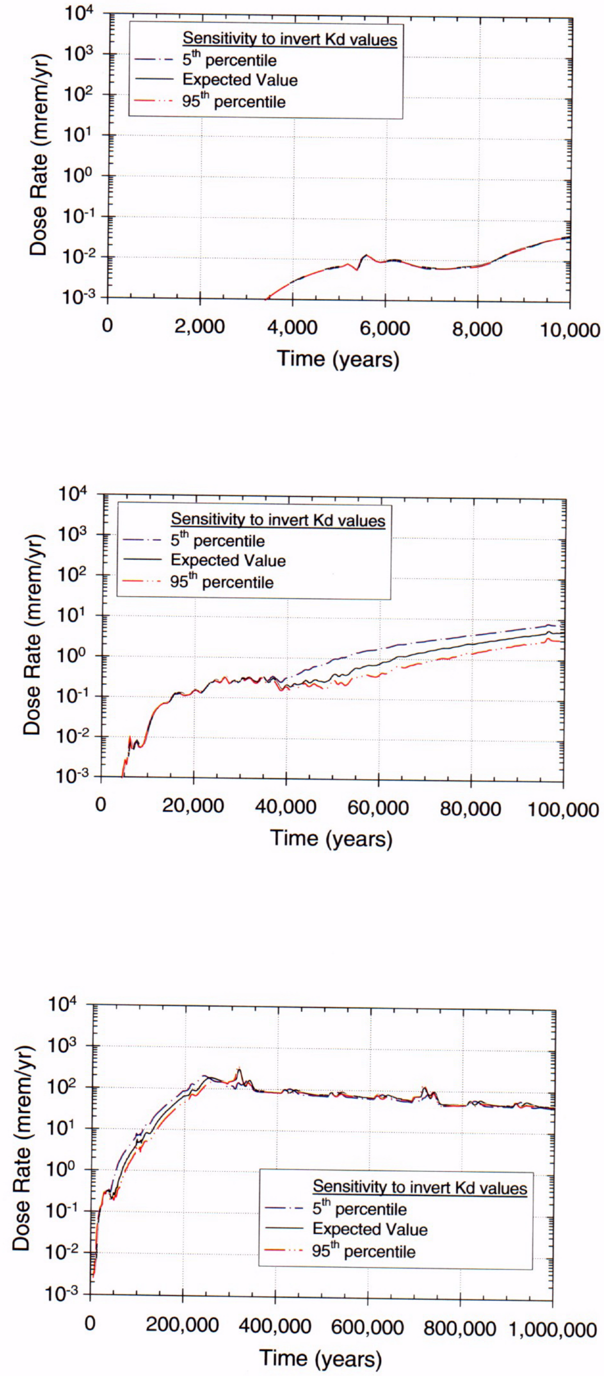

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Figure 5-37. Effect of Radionuclide Distribution Coefficients in the Concrete Invert on Total Dose Rate at 20 km (12 miles)
Comparison of base case expected-value K_ds with the base case 5th and 95th percentile values. The primary effect is from the neptunium K_d.

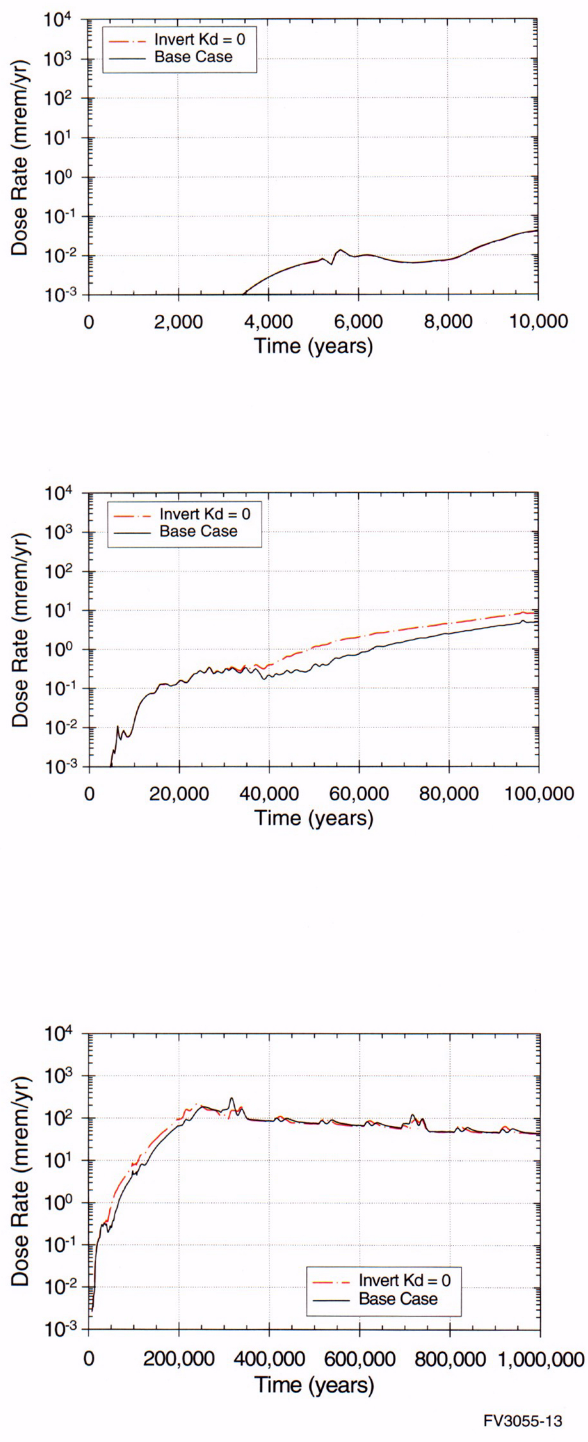

Figure 5-38. Sensitivity of Total Dose Rate to an Alternative Engineered Barrier System Transport Model that Assumes the Radionuclide K_ds in the Invert are Equal to Zero
In the top figure, the two curves overlay.

summary, the retardation in the invert appears to have little significance to total dose, and this is in spite of the fact that the expected-value K_d in the base case is quite high.

5.5.7 Comparison of the Surrogate U.S. Department of Energy Spent Nuclear Fuel to DOE Spent Nuclear Fuel Total

The base case analyses reported in Sections 3.5, 4.2, and 4.3 used a surrogate inventory for DOE spent nuclear fuel rather than explicitly modeling each of more than 250 types of the fuel. The surrogate was based on the key dose contributors from the 15 categories of DOE spent nuclear fuel that were determined in the original inventory. To determine the key dose contributors, each individual DOE spent nuclear fuel category was analyzed by placing it in the environment of the base case, one category at a time, and calculating the expected dose to humans located 20 km (12 miles) downgradient from the repository. The 2,333 metric tons of heavy metal (MTHM) of surrogate have a radionuclide inventory that is a weighted average (on an MTHM basis) of the radionuclide inventories of Categories 1, 4, 5, 6, 8, and 11. These six categories were found to contribute significantly to the dose from all DOE spent nuclear fuel (Duguid et al. 1997, pp. 4-1 to 4-10, 6-2 to 6-3). Because the majority of the DOE spent nuclear fuel is metallic, the metallic dissolution model was assumed for the surrogate. In addition to these six categories, Categories 7 and 16 were also found, in the current analyses, to contribute significantly to the dose from all DOE spent nuclear fuel (CRWMS M&O 1998i). In the base case, these categories are represented by the surrogate spent nuclear fuel, which would yield conservative results. (For more detail on this analysis, see Chapter 6 of *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* [CRWMS M&O 1998i].)

The dose rate from each DOE spent nuclear fuel category is presented in Figure 5-39 over the first 100,000 years after repository closure. Figure 5-39 also compares the total dose from the surrogate DOE spent nuclear fuel to the total DOE spent

C-94

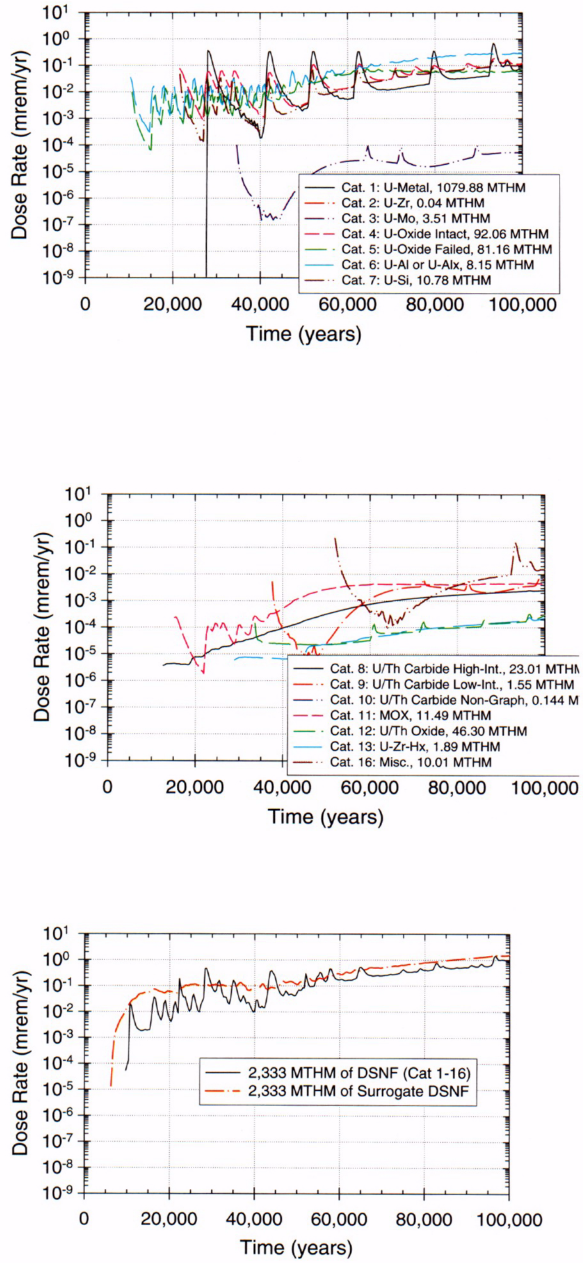

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Figure 5-39. Expected-Value Total Dose-Rate History at 20 km (12 miles) over 100,000 Years for Sixteen Categories of U.S. Department of Energy Spent Nuclear Fuel
Total dose rate for all DOE spent nuclear fuel, found by summing the individual categories, compared to the surrogate DOE spent nuclear fuel (bottom figure). Fuel is assumed to be exposed upon waste package failure (no credit for cladding).
(DSNF—DOE Spent Nuclear Fuel)

nuclear fuel, where the latter is defined as the sum of the dose rates from the various categories 1-16. The spikes on the total DOE spent nuclear fuel curve are caused by individual package failures of DOE spent nuclear fuel, with the highest spikes being from Category 1. They occur because of the small number of packages in some DOE spent nuclear fuel categories (e.g., Category 1 has 107 packages). In contrast, the surrogate spent nuclear fuel curve is smoother because of the larger number of disposed packages (2,546 waste packages).

The contributions to total dose from naval spent nuclear fuel (Category 15) that had not been analyzed previously were found to be insignificant (CRWMS M&O 1998i).

5.5.8 Comparison of Plutonium Waste Form with Commercial Spent Nuclear Fuel Equivalent Waste Form

Another waste form currently planned for disposal in the repository is plutonium waste. The plutonium waste consists of two subtypes: a Zircaloy-clad, mixed uranium-plutonium oxide spent nuclear fuel, and a can-in-canister, ceramic waste, which is a plutonium ceramic in cans that are encapsulated in high-level radioactive waste in a standard high-level radioactive waste canister. The cans of ceramic comprise approximately 12 percent of the canister volume, and four of these canisters are assumed to be disposed of in a high-level radioactive waste package. The mixed uranium-plutonium oxide fuel contains approximately 5 percent plutonium and is assumed to be used as fuel in a standard, pressurized water reactor. The spent nuclear fuel is assumed to be disposed of in 21 assembly, pressurized water reactor waste packages. There are 75 packages of mixed uranium-plutonium oxide spent nuclear fuel and 159 packages of can-in-canister ceramic (CRWMS M&O 1998i).

The effects of disposal of the 50 tons of surplus plutonium was analyzed by simulating the emplacement of the plutonium waste forms, one at a time, in the base case environment and analyzing the expected value dose history 20 km (12 miles) from the repository (CRWMS M&O 1998i).

C-95

Figure 5-40 compares the doses from 33 tons of plutonium as mixed uranium-plutonium oxide spent nuclear fuel and 17 tons of plutonium as can-in-canister ceramic with equivalent commercial spent nuclear fuel and high-level radioactive waste.

A comparison of the mixed uranium-plutonium oxide spent nuclear fuel with an equivalent amount of commercial spent nuclear fuel shows that the dose from both is nearly identical, with the mixed uranium-plutonium oxide being negligibly higher. A comparison of the can-in-canister ceramic with an equal number of packages of high-level radioactive waste indicates that the dose from the high-level radioactive waste is negligibly higher than from the can-in-canister ceramic. These results show that the dose attributed to mixed uranium-plutonium oxide fuel and can-in-canister ceramic is essentially the same as that from commercial spent nuclear fuel and high-level radioactive waste, respectively. These results can be interpreted to mean that the effects on dose from disposal of plutonium are not significant, because the spent nuclear fuel equivalent and equivalent number of high-level radioactive waste packages would have been disposed of anyway.

5.6 UNSATURATED ZONE TRANSPORT

This section examines the sensitivities of the total system performance to variations in matrix diffusion, sorption, and a coupled sorption and source term scenario. These sensitivity analyses are intended to complement the unsaturated zone subsystem calculations presented in Section 3.6 and provide information on how changes in the subsystem affect performance of the total system.

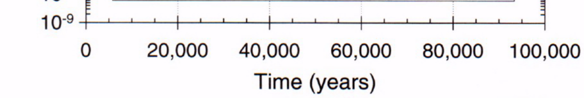

Figure 5-40. Comparison of Total Dose Rate for Plutonium Waste Forms (Mixed Oxide Fuel and "Can-in-Canister")
(CSNF—commercial spent nuclear fuel; HLW—high-level radioactive waste; MOX—mixed oxide fuel)

5.6.1 Sensitivity to Matrix Diffusion

Analyses of matrix diffusion sensitivity for unsaturated zone flow were carried out for different infiltration rates and conceptual models. The relationship between matrix diffusion and flow is important because the relative rates of these processes influence how matrix diffusion affects unsaturated zone transport. In particular, the relative rates of advective transport in the fractures to diffusion in the matrix (coupled with matrix sorption) determine how strongly matrix diffusion influences transport in the unsaturated zone.

The base case, expected-value dose-rate history is shown in Figure 4-12. This figure shows that early dose (up to about 50,000 years) is dominated by technetium; after that time, the dose is dominated by neptunium. The dominant radionuclide for dose affects the sensitivity analyses discussed below because of the differences in matrix diffusion and sorption between these radionuclides (see Section 3.6). Sorption enhances the effects of matrix diffusion because it sharpens concentration gradients, the driving force for diffusion, between the fractures and matrix. Technetium is nonsorbing and in the aqueous phase is expected to be in the form of the negatively charged pertechnetate anion, TcO_4^- (Triay et al. 1997, p 177). Mineral surfaces also are commonly negative in charge, so pertechnatate tends to be repelled slightly by the rock matrix surfaces (ibid, p.182). Both these characteristics of technetium lead to less matrix diffusion. Neptunium is weakly sorbing on the different rock matrix types in the unsaturated zone. For oxidizing conditions at values of pH less than about 7, the aqueous form of neptunium is expected to be predominantly the positively charged neptunyl cation, NpO_2^+ (ibid, p. 124, Table 47). Therefore, neptunium transport is expected to be more strongly influenced by matrix diffusion. Although values of pH are likely to be larger than 7 (see

C-96

Section 3.3), we have used the matrix diffusion coefficient for a positively charged species as a conservative measure.

Figure 5-41 shows the change in dose at the 20-km (12-mile) boundary for the expected value base case with and without matrix diffusion. In general, matrix diffusion is found to have little influence on dose; some slight variations at very early times (< 5,000 years) and then at longer times (about 70,000 to 250,000 years) are seen in the figure. Matrix diffusion is expected to have greater influence at the leading edge of the releases because the concentration gradients at the front are larger. The slight variation in responses at longer times is believed to be caused by the dominance of neptunium for total dose after about 50,000 years. Before this time, dose is dominated by technetium. The greater sensitivity of neptunium to matrix diffusion (after the leading edge of the concentration front passes through the system) is expected because of the differences discussed above the respect to matrix diffusion and sorption. The fact that matrix diffusion has much less effect on dose at the 20-km (12-mile) boundary than on the unsaturated zone radionuclide transport results (see Section 3.6) suggests that other aspects of the total system, such as engineered barrier system releases and saturated zone transport, tend to dominate the total system response.

The effect of matrix diffusion on other flow models besides the expected-value base case model was also analyzed, but not shown here because of the negligible effect. The other four flow fields in the base case (see Section 5.1) showed similar behavior to the expected-value flow field (the "base infiltration with mean fracture alpha" case), with relatively little effect on total dose rate from matrix diffusion in the unsaturated zone. The DKM/Weeps model also showed similar behavior to the expected-value base case flow field.

5.6.2 Sensitivity to Sorption

This section considers the sensitivity of performance to sorption in the unsaturated zone and does not consider changes to sorption in the saturated zone.

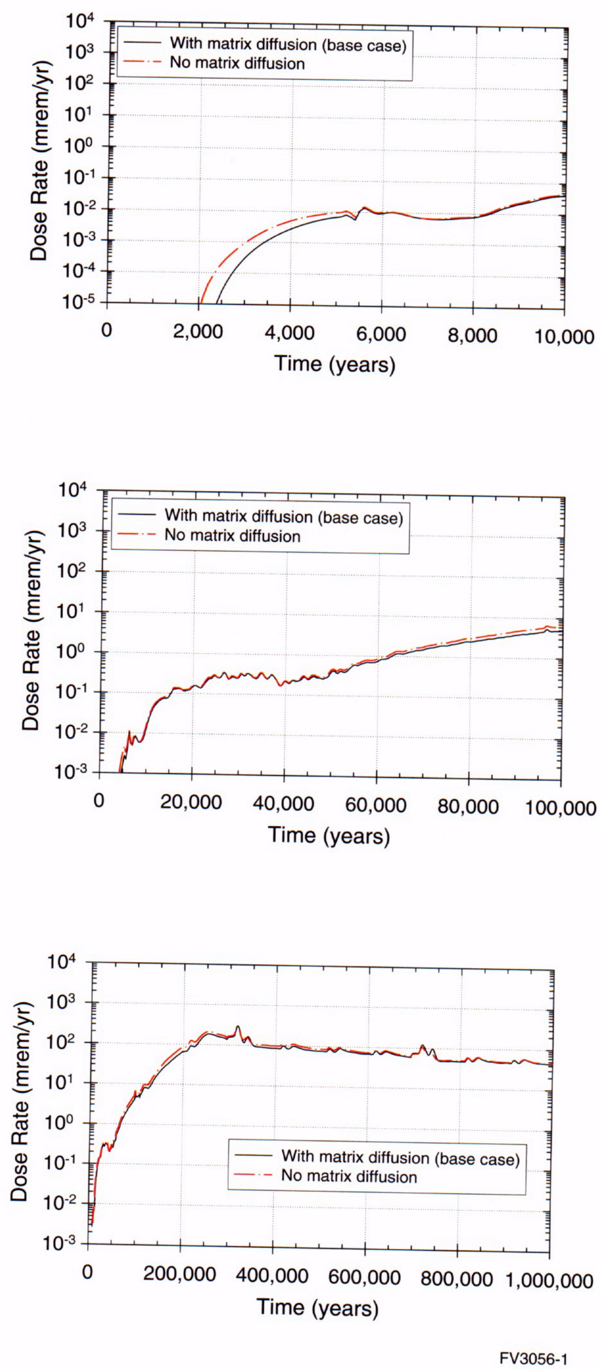

Figure 5-41. Comparison of Zero-Matrix-Diffusion (in the Unsaturated Zone) Model with Base Case Model
Effect on total dose rate at 20 km (12 miles) for three different periods.

C-97

The first sensitivity examined is to the uncertainty ranges for the distribution or sorption coefficients (K_ds) in the base case, specifically for neptunium, plutonium, uranium, selenium, and protactinium. Figure 5-42 shows the total dose rate histories resulting from using the 5th and 95th percentile values for these K_ds. The effect is negligible.

To account for other effects on sorption besides those encompassed by the base case ranges of the K_ds, an extreme alternative sorption model was examined. In particular, a model of zero sorption for the actinides (neptunium, uranium, protactinium, and plutonium) in the unsaturated zone is examined. One of the reasons that actinide sorption could disappear is that the repository may create thermal-chemical effects that could reduce sorption. One interaction that may lead to reduced actinide sorption in the unsaturated zone is an increase in pH. Higher values of pH may occur because of the interaction of water with concrete in the repository (see Section 3.3). The higher pH is believed to reduce sorption through geochemical effects on speciation of the actinides. For example, at lower values of pH (below 7), neptunium is expected to be primarily NpO_2^+, while at higher values of pH the dominant species is $NpO_2(CO_3)$ (Triay et al. 1997, p. 124, Table 47). The positively charged species of neptunium has a weak tendency to sorb onto matrix rock, but the negatively charged species is essentially nonsorbing.

Figure 5-43 compares total dose rates over the three time frames for the base case and the zero sorption case. It indicates that the early doses are not affected by sorption (primarily because of technetium), but that sorption helps to reduce the total dose rate between 50,000 and 250,000 years (primarily because of neptunium and plutonium) by about a factor of three.

The effects of neptunium sorption for this alternative model are given in Figure 5-44 over the first 100,000 years. When compared to the base case, the effect of K_d=0 of neptunium is found to be relatively small because neptunium is only weakly sorbing in the base case. Similar results are found

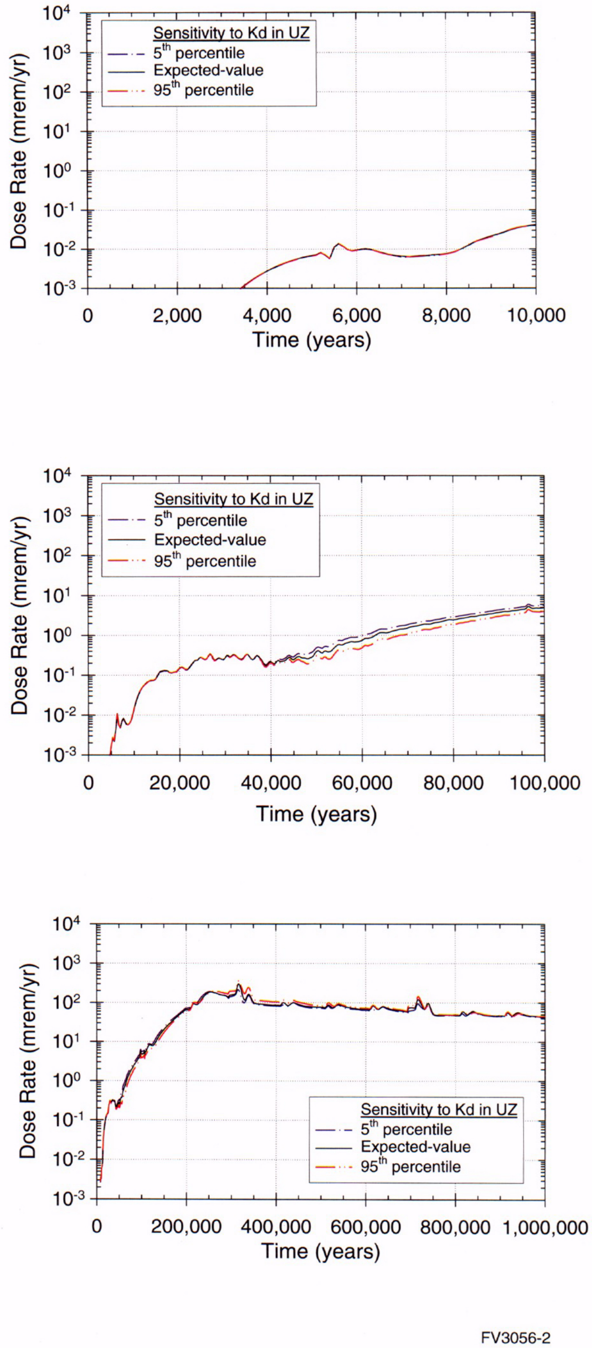

Figure 5-42. Effect of Radionuclide Distribution Coefficients in the Unsaturated Zone Matrix on Total Dose Rate at 20 km (12 miles)
Comparison of base case expected-value K_ds with the base case 5th and 95th percentile values. The primary effect is from the neptunium K_d.

C-98

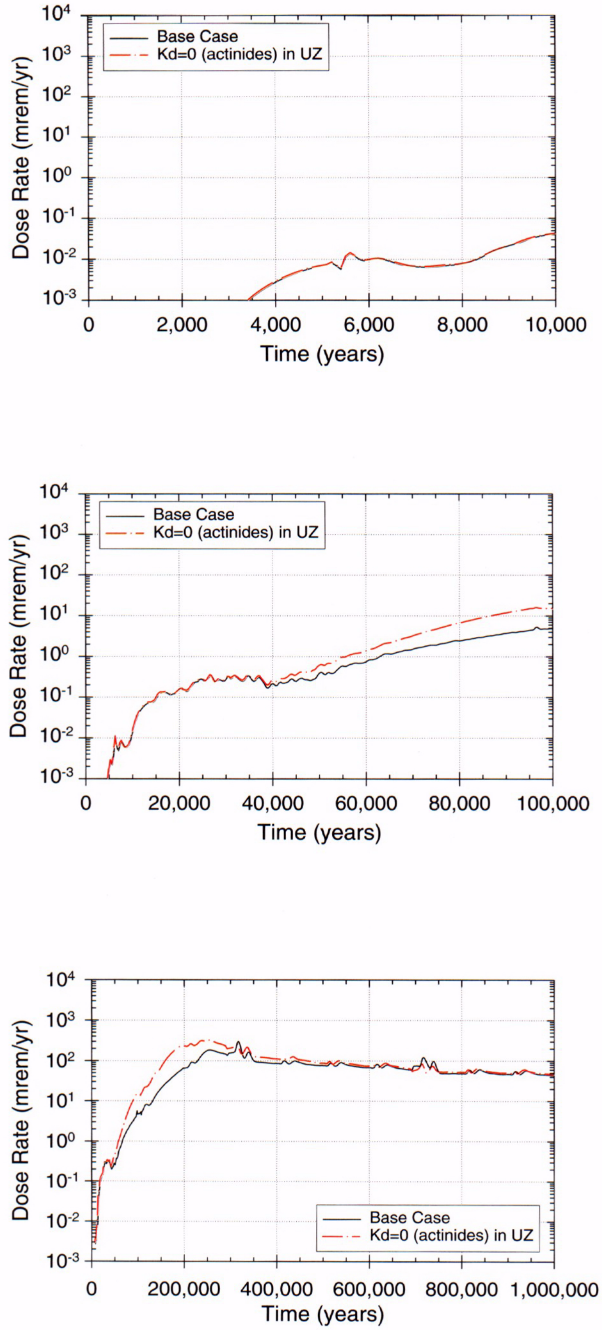

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Figure 5-43. Sensitivity of Total Dose Rate to an Alternative Unsaturated Zone Transport Model that Assumes the Actinide K_ds in the Unsaturated Zone Rock Matrix are Equal to Zero
The primary effect is from the plutonium K_d.

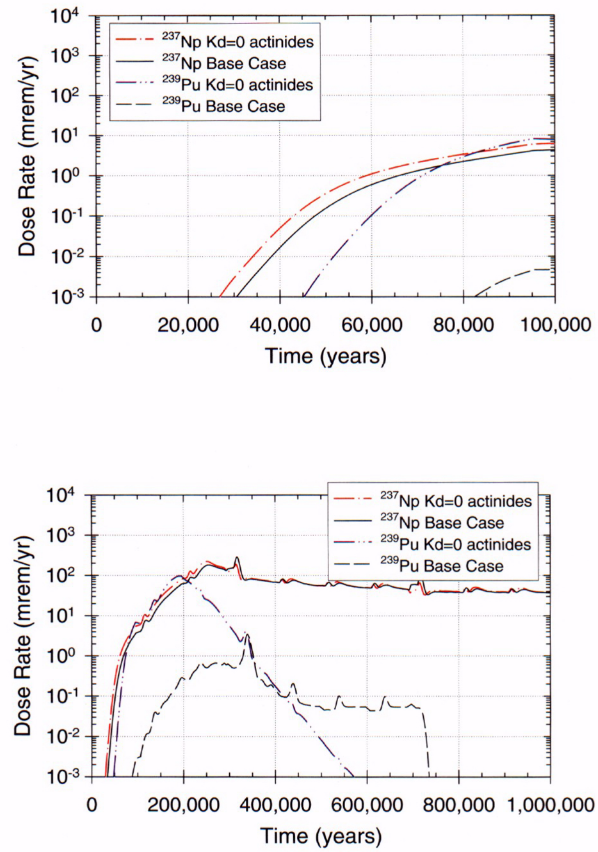

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Figure 5-44. Sensitivity of Neptunium-237 and Plutonium-239 Dose Rate to an Alternative Unsaturated Zone Transport Model that Assumes the Actinide K_ds in the Unsaturated Zone Rock Matrix are Equal to Zero

for uranium, which is also a weakly sorbing element.

The effects of sorption on plutonium transport are more complex. Plutonium is a strongly sorbing radionuclide, but is also subject to colloidal transport. A portion of the colloid interaction is believed to be caused by sorptive mechanisms. Sorption on the rock matrix retards plutonium transport, while sorption on colloids facilitates plutonium transport. Therefore, the sensitivity of plutonium transport to sorption is a result of two competing effects. The overall effect of eliminating sorption on plutonium transport is shown in Figures 5-44 and 5-45 for plutonium-239 and plutonium-242, respectively. For both plutonium

C-99

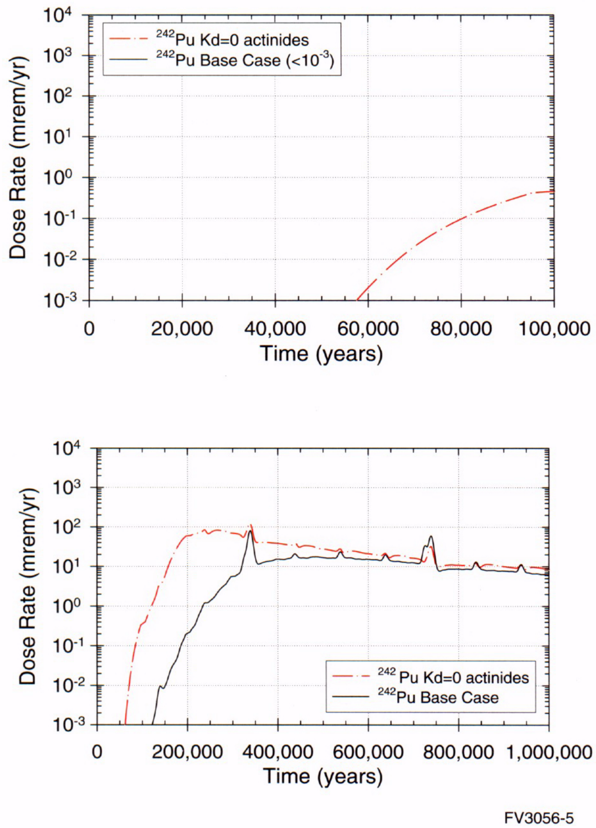

Figure 5-45. Sensitivity of Plutonium-242 Dose Rate to an Alternative Unsaturated Zone Transport Model that Assumes the Actinide K_ds in the Unsaturated Zone Rock Matrix are Equal to Zero

isotopes, the elimination of sorption causes higher dose rates. In fact, plutonium-239 dose rates slightly exceed those of neptunium-237 for the zero-sorption model between 100,000 and 200,000 years. These sensitivity results indicate that the sorption of aqueous plutonium on the rock matrix is dominant over the sorption of plutonium on colloids. Also, it is evident that the factor-of-3 increase in total dose indicated on Figure 5-43 between 100,000 and 200,000 years is caused by the plutonium isotopes becoming as important as neptunium-237.

5.6.3 Sensitivity to Combined Effects of Source Term and Unsaturated Zone Sorption

In addition to reducing sorption, increased pH from concrete dissolution may also promote waste package corrosion and waste form dissolution, as discussed in Sections 5.3 and 5.4, accelerating releases from the engineered barrier system. The dose effects at 20 km (12 miles) caused by the combined effects of zero sorption in the unsaturated zone and concrete-modified waste package and waste form degradations are shown in Figure 5-46. Dose is much higher before 10,000 years.

This early peak in dose is caused by greater releases of technetium from the engineered barrier system (see Section 5.3). Similarly to Figures 5-44 and 5-45, neptunium and plutonium are the primary causes of the later increase in doses. These increases in dose for neptunium and plutonium may be attributed to a combination of greater transport rates (see Section 5.6.1) and greater releases from the engineered barrier system (see Section 5.3). Changes in releases from the engineered barrier system indicate that plutonium-242 would always provide a greater portion of the dose than neptunium. However, sorption in the saturated zone is found to retard plutonium release to the accessible environment sufficiently so that the neptunium, which is less strongly sorbing, provides a greater portion of the dose following the technetium peak but before the arrival of plutonium.

By comparing Figures 5-14 and 5-43, it is apparent that most of the change in total dose rate for this alternative model is due to the effect on engineered barrier system releases up until 50,000 years and due to the effect on sorption in the unsaturated zone after 100,000 years. Between those two times, it is a combination of the two effects.

C-100

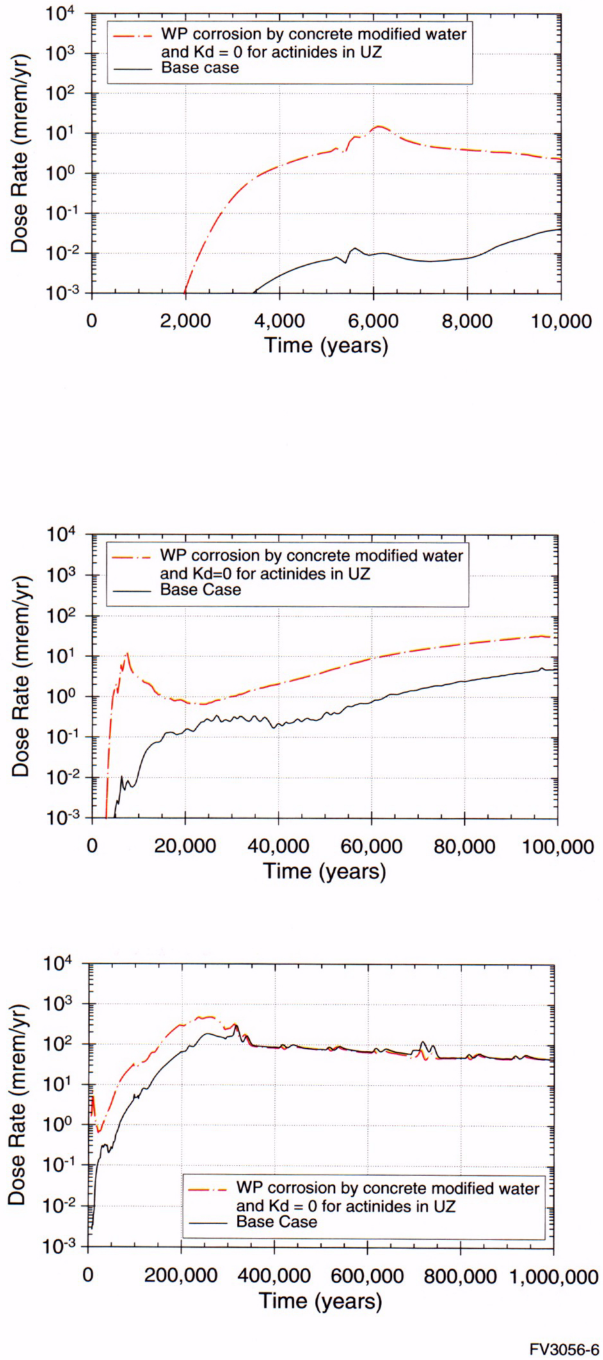

Figure 5-46. Sensitivity of Total Dose Rate to the "Alkaline Plume" Model
This model is a result of concrete degradation in the drift which raises the pH in the engineered barrier system and in the unsaturated zone. This causes an increased rate of waste package and waste form degradation and decreased (zero) sorption in the unsaturated-zone. Compare Figures 5-14 and 5-42. (UZ—unsaturated zone)

5.7 SATURATED ZONE FLOW AND TRANSPORT

Three sensitivity studies were conducted to look at the effects of base case assumptions about saturated zone flow and transport. The sensitivity studies addressed the importance of the dilution factor, the fraction of the saturated-zone flow path in alluvium, and how six flow tubes are combined to calculate the final concentration.

Assumptions about the flow model and parameters were not addressed because estimated variation in these areas would affect only radionuclide travel times and not significantly affect dilution and peak dose rate. Therefore, they are relatively less important. Also, changes in the effective-porosity parameter cause changes in the groundwater velocity. The effective porosity was considered probabilistically in the base case (Section 3.7). Assumptions about transport variables (other than the dilution factor) were not addressed for two reasons:

- These parameters also primarily influence radionuclide travel time, not dose rate
- They are defined with probability distributions and covered in the probabilistic analyses (Section 4.3)

One issue that cannot be addressed yet is the amount of dilution at the interface between the unsaturated and saturated zones. No additional dilution is allowed when contaminated water from the unsaturated zone enters the saturated zone. However, the contamination is assumed to uniformly spread through the water in each of the six areas at the base of the unsaturated zone so that dilution is implicitly considered. This assumption might overestimate dilution when a small number of containers release waste. As the number of releasing containers increases, the assumption becomes more appropriate.

5.7.1 Sensitivity to Dilution

The first sensitivity study addresses how the variation in the dilution-factor distribution affects

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dose rate. Figure 5-47 shows the results of the expected-value base case. Also shown are two calculations that are the same as the expected-value base case, except that one calculation uses the 5th-percentile value of the base case dilution-factor distribution and the other calculation uses the 95th-percentile value. In the dilution-factor distribution, the median value is 10; the 95th-percentile value is a dilution factor of 49, or approximately a factor of 5 above the median. The 5th-percentile value is a dilution factor of 1.7, approximately a factor of 6 below the median. The dose is proportional to the radionuclide concentrations in the groundwater, and the concentration is inversely proportional to the dilution. The 95th-percentile dilution factor does decrease the expected-value-case dose rate by about a factor of 5. The 5th-percentile dilution factor does not increase the dose by a factor of 6. The 5th-percentile dilution is small enough so that the usual method of calculating the final concentration—adding the six stream tubes—exceeded the maximum undiluted concentration in the stream tubes (Sections 3.7.2.3 and 5.7.3). Hence, the dose-rate curve for the 5th-percentile dilution factor is calculated using the maximum undiluted concentration. It is significant that the dose rate does not increase in proportion to the dilution factor at very small dilution factors. The final difference between the 5th-percentile and 95th-percentile curves ranges between approximately a factor of 10 at early times and during superpluvials, and approximately a factor of 7 at other times. This difference is enough to cause the dilution factor to be one of the most important parameters (Section 4.3).

5.7.2 Sensitivity to Alluvium Fraction

The second sensitivity study addresses how the fraction of the saturated zone flow path in alluvium affects dose rate. Alluvium has higher effective porosity and higher radionuclide retardation as compared to the fractured tuff, so transport tends to be significantly slower through the alluvium. Figure 5-48 shows dose-rate history curves for the expected-value base case plus two additional cases defined by setting the alluvium fraction to the 5th percentile and the 95th percentile of its base case probability distribution while keeping all other

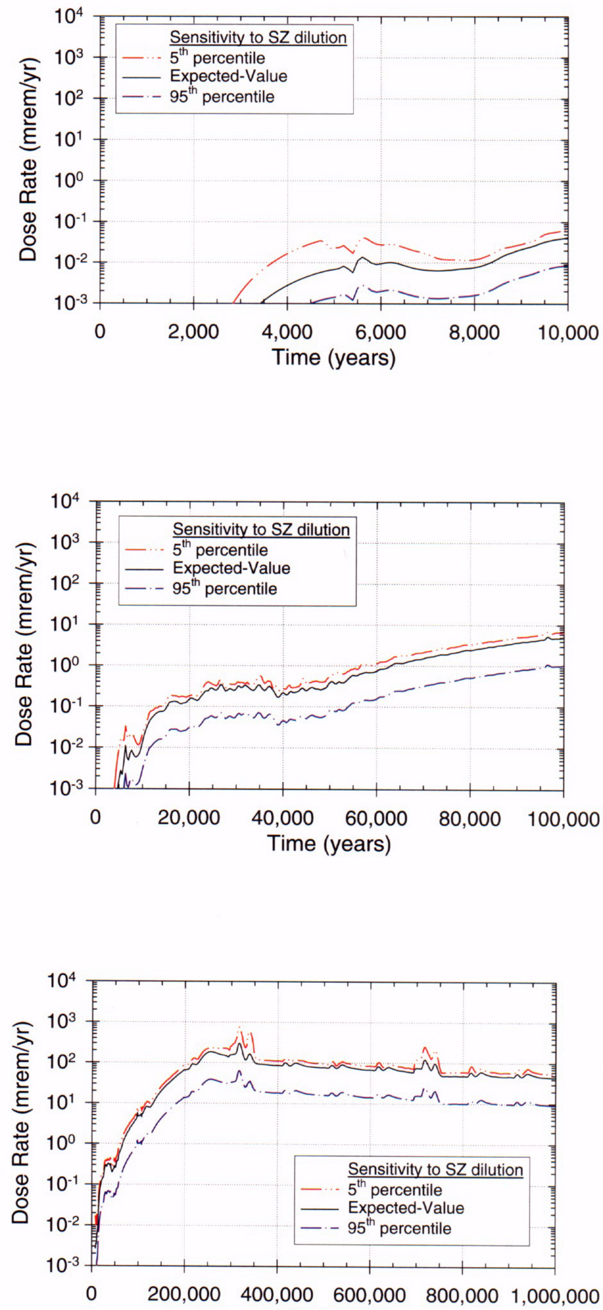

Figure 5-47. Total Dose-Rate History Curves for the Expected-Value Base Case and Cases that Have Saturated Zone Dilution Factor at the 5th and 95th Percentiles of its Base Case Distribution (SZ—saturated zone)

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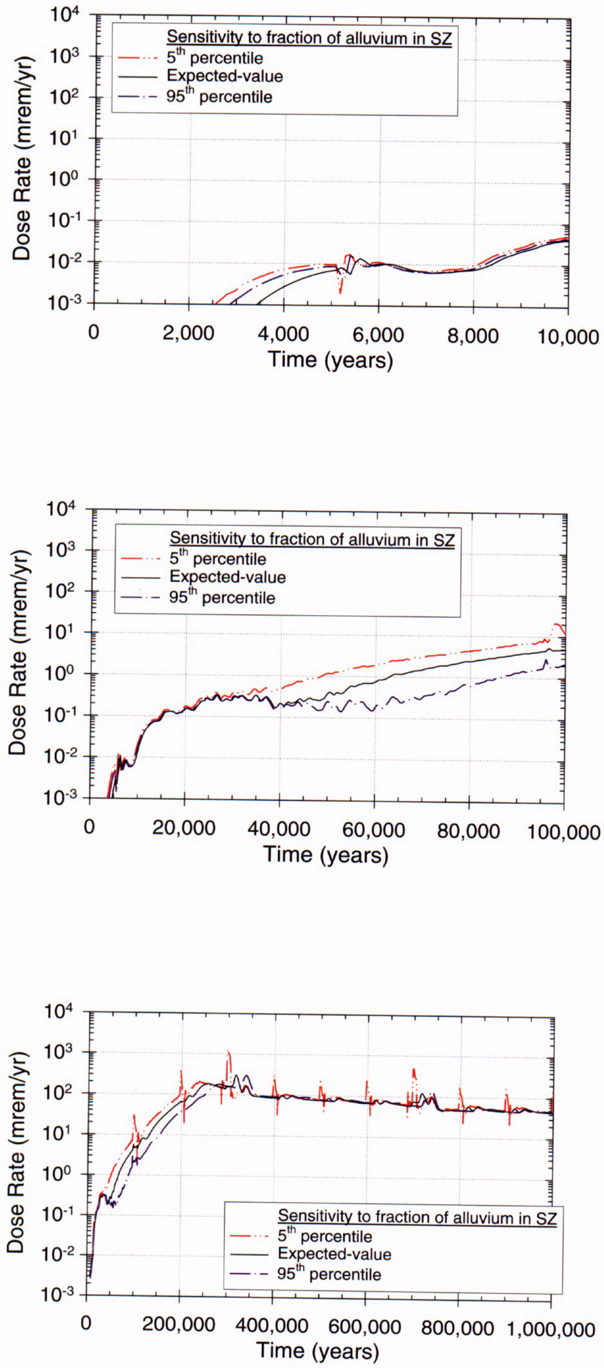

Figure 5-48. Total Dose-Rate History Curves for the Expected-Value Base Case and Cases that Have the Fraction of the Saturated Zone Flow Path in Alluvium at the 5th and 95th Percentiles of its Base Case Distribution
(SZ—saturated zone)

parameters fixed at their expected values. Figure 5-48 shows that alluvium fraction affects the dose rate by a moderate amount. The most interesting behavior is shown in the 1-million-year plot (Figure 5-48, bottom). The spikes caused by climate changes are much more pronounced in the fifth-percentile case. This behavior results because the alluvium in the flow path has a damping effect on the climate-change spikes, so when there is less alluvium the spikes are larger.

5.7.3 Sensitivity to Method of Flow-Tube Combination

The third sensitivity study examines the effect on the dose-rate results of how the six one-dimensional flow tubes are combined, for the saturated zone, to estimate the final, diluted concentration at the biosphere/geosphere interface. Radionuclide concentrations at a distance of 20 km (12 miles) were calculated separately for each of the six flow tubes (Section 3.7). The goal is to preserve the spatial variability but allow diffusion and dispersion out of the individual flow tubes and potentially into neighboring flow tubes. Three methods are considered for calculating the concentration used for determining dose:

- The final concentrations in the six flow tubes are summed. If the sum is larger than the greatest initial concentration in one of the flow tubes, then that initial concentration is substituted for the result. It is not physically realistic for concentrations to increase above the initial maximum concentration. This method overestimates the concentration; it is the method used in the base case.

- The final concentration in the flow tube that is the greatest of all the flow tubes is selected as the maximum concentration. This method underestimates the final concentration because radionuclides from other flow tubes might diffuse or disperse into the selected flow tube. (By the principle of linear superposition of solutions, two spreading plumes that overlap must have at least as high a maximum concentration as if they did not overlap.)

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- One flow tube is used in place of the six flow tubes to calculate the final concentration. This method also underestimates the final concentration, because initially all radionuclides are distributed in all the water from the unsaturated zone, thereby ignoring spatial variability and omitting any potential high-concentration regions.

The results of the concentration-combination study are presented in Figure 5-49. The first method is incorporated in the expected-value base case. The other methods are modifications of the expected-value base case. As anticipated, the first method—summing the concentrations—causes the greatest doses. The second method—using the highest concentration flow tube—causes doses that are approximately a factor of four below the first method. The third method—using one flow tube—causes doses that are approximately a factor of six below the first method. The relationship depends on the distribution of radionuclides in the flow tubes at the boundary between the unsaturated and the saturated zones. The calculated dose depends on the method of determining the final concentration. However, the differences in dose are less than the differences caused by parameters such as the dilution factor that are significant to the final results (compare Figures 5-47 and 5-49).

5.8 BIOSPHERE

Three sensitivity studies were conducted to look at the effects of assumptions about the biosphere on the TSPA calculations. Other assumptions internal to the biosphere modeling that affected calculation of biosphere dose conversion factors also were considered (see Section 3.8.3).

The sensitivity studies address how the variability in biosphere dose conversion factors influences the final calculated dose rates, how assumptions related to dilution at the well and in the biosphere affect the calculated dose rates, and how assumptions about the critical group affect calculated dose rates.

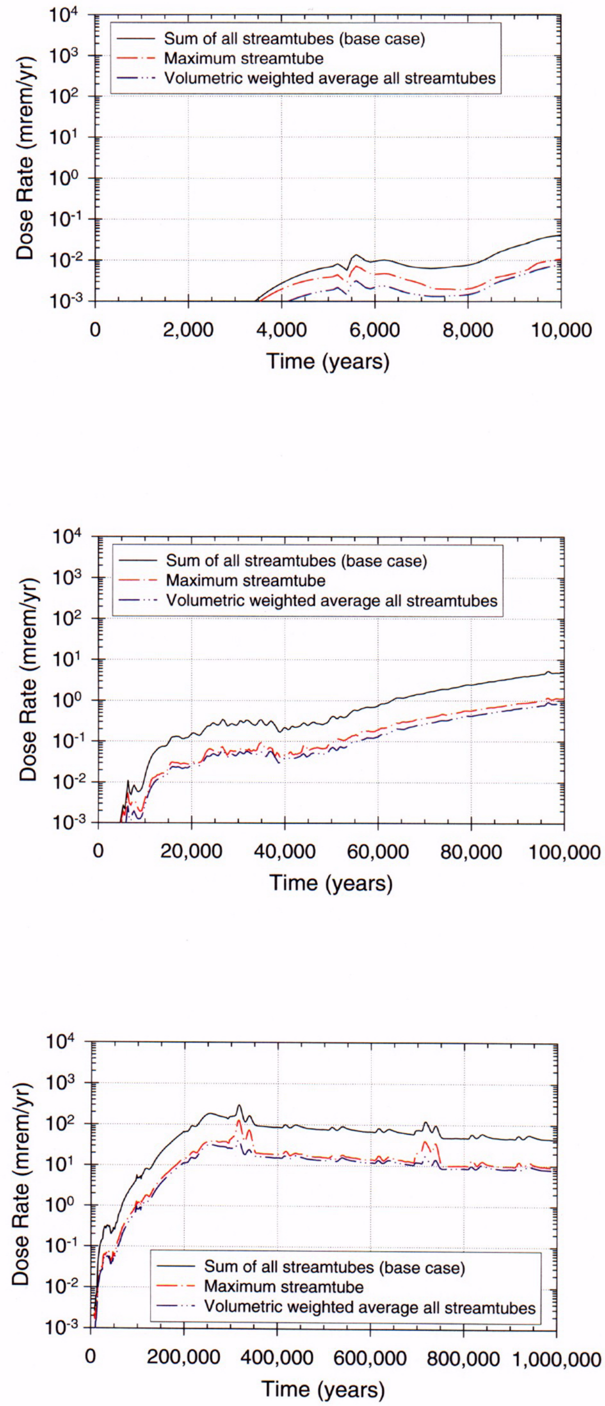

Figure 5-49. Total Dose-Rate History Curves for the Expected-Value Base Case and for Two Sensitivity Cases that Use Different Methods for Combining the Six Flow Tubes Used to Model the Saturated Zone

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5.8.1 Sensitivity to Biosphere Dose Conversion Factor

The first sensitivity study addresses how the final dose calculation is affected by the spread in the distributions used to define the biosphere dose conversion factors. Figure 5-50 shows the results of the expected-value base case. Also shown are two calculations that are the same as the expected-value base case, except that in one the 5th-percentile values of each biosphere dose conversion factor distribution for each radionuclide is used and, in the other calculation, the 95th-percentile values are used. In the figure, using the 5th-percentile, biosphere dose conversion factors decreases expected-value-case dose rates by about a factor of 3; using the 95th-percentile biosphere dose conversion factors increases the dose rates by about the same amount. The spread in most of the biosphere-dose-conversion-factor distributions is about an order of magnitude (a factor of 10), and thus the difference in doses calculated by the 5th-percentile and 95th-percentile values also is about an order of magnitude.

The three curves shown in Figure 5-50 have an identical shape. The dose is proportional to the concentration of radionuclides in the groundwater, and the biosphere dose conversion factors for the radionuclides are the constants of proportionality. Although this is a linear relationship, when combined with the relatively large uncertainty in biosphere dose conversion factors as shown by the order-of-magnitude spreads in the distributions, it is enough to cause the biosphere dose conversion factor to be an important parameter in TSPA-VA. (That is, out of 177 parameters defined with probability distributions in the base case, the biosphere dose conversion factors are number three in importance over the one-million-year time frame, as shown in Figure 4-34.)

5.8.2 Sensitivity to Dilution at the Well and in the Biosphere

The second sensitivity study examines assumptions made in the base case analyses concerning well-water withdrawal, well location, and food-source

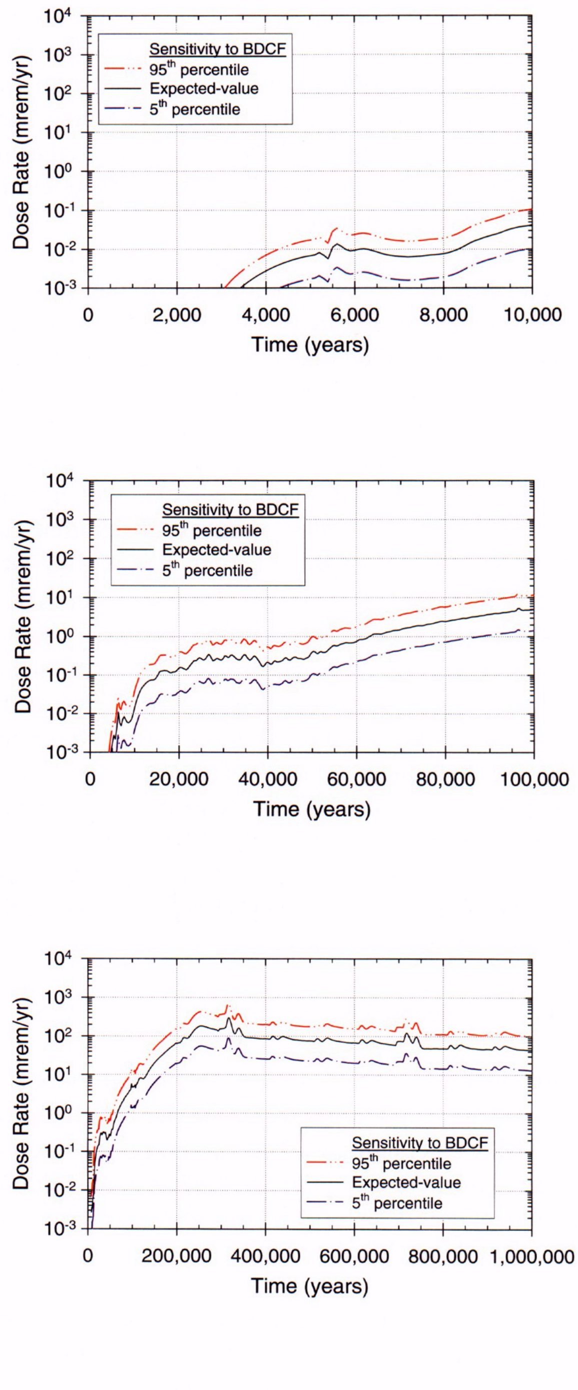

Figure 5-50. Total Dose-Rate History Curves for the Expected-Value Base Case and Cases that Have Biosphere Dose Conversion Factors at the 5th and 95th Percentiles of Their Base Case Distributions (BDCF—biosphere dose conversion factors)

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location; these assumptions are related to the choice of an individual-dose performance measure. Some of these assumptions are as follows:

- The individual's water source is always at the point of maximum contamination in the aquifer.

- There is no dilution during withdrawal of water from the aquifer; that is, there is no mixing of contaminated water with uncontaminated water when the water is pumped from the ground or when the water is stored in a tank.

- The locally produced foodstuffs that this individual consumes, as determined by a survey of existing inhabitants of the Amargosa Valley region (Section 3.8.1), were all grown with this maximally contaminated groundwater. In other words, consumables, possibly grown away from contaminated groundwater, but still in the Amargosa Valley region, were considered to be contaminated.

If the plume of contaminated groundwater is large and dispersed, these assumptions are reasonable. In the saturated zone modeling, the contaminated groundwater travels in flow tubes and is typically diluted by a factor of 10. The original plume has cross-sectional dimensions of about 3,000 m (10,000 ft) horizontally and 10 m (30 ft) vertically. The plume at 20 km (12 miles) downgradient has an undefined cross section, but with a dilution factor of 10, it might have dimensions of about 10,000 m (30,000 ft) horizontally and 30 m (100 ft) vertically. At the estimate groundwater flux of 0.6 m/year (2 ft/year), such a plume would constitute approximately 180,000 m^3/year (50 million gal/year) of water. (This approximation is somewhat less than the volume actually used in the expected-value base case.)

To examine the assumptions that all drinking water and all local consumables are produced using well water containing the highest concentration of radionuclides, the average dose rate per person is introduced. To calculate an average dose rate per person, all contamination is assumed to be spread equally in all water available to a group of people. Also, each member of the group is assumed to use the same amount of water—the average water usage per person. For a given volume of contaminated water, the size of group of people can be estimated. For a given mass of radionuclides, the radionuclide concentration—and thus the average dose rate per person—can be estimated.

The mass of each radionuclide reaching the 20-km (12-mile) distance from Yucca Mountain at a given time can be taken from the TSPA-VA expected-value base case results. This mass is dissolved in a certain amount of water, for example, if the approximate base case volume is assumed, then this mass is dissolved in 180,000 m^3/year of water directly linked to the repository. If, however, it is assumed that this mass is dissolved in all of the groundwater that is currently being pumped from the Amargosa Valley, which includes water sources not linked to the repository, then this mass is dissolved in an estimated 12 million m^3/year (3 billion gal/year), resulting in a lower concentration of radionuclides in water. Note that based on this estimate of present-day water production, the average water usage for a member of the Amargosa Valley population (approximately 1,300 people) is about 9,300 m^3/year or 2.5 million gal/year.

The peak radionuclide release over a one-million-year period is estimated to occur 317,000 years in the future and the major contributor to the dose rate is neptunium-237, which reaches 20 km (12 miles) at the peak rate of 12 g/year. If this mass of radionuclide is dissolved in the amount of water corresponding to the current estimated volume of water produced in Amargosa Valley instead of the base case volume, then the resulting radionuclide concentration is 1.0×10^{-6} g/m^3. The dose rate resulting from using this contaminated water is found by multiplying the radionuclide concentration by the biosphere dose conversion factor, which for neptunium-237 is 4.6×10^{6} mrem/year per g/m^3. The result is an average peak dose rate of 4.6 mrem/year. If, however, the approximate base case volume is assumed, the resulting neptunium-237 concentration is 6.7×10^{-5} g/m^3, and a corresponding average peak dose rate is 308 mrem/year.

(This dose rate does not correspond exactly to the value calculated for the expected-value base case described in Section 4.2. The peak dose rate in the expected-value base case occurred during the long-term-average climate and was calculated for a larger groundwater flux. However, the concentrations for the various flow tubes used were combined in the expected-value base case, yielding a similar concentration and dose rate to the values presented here.) This sensitivity analysis shows that dose rate is 67 times higher for the base case than if the entire water-production dilution is assumed. Based on the current Amargosa Valley water usage per resident (9,300 m^3/year), the approximate base case volume of groundwater (180,000 m^3/year) could only support about 20 people. Figure 5-51 presents the relationship between the average dose rate per person and the size of the group using contaminated water, calculated using the peak radionuclide release from the expected-value base case results for the one-million-year period.

This analysis indicates that assumptions related to how radionuclides are distributed in the biosphere

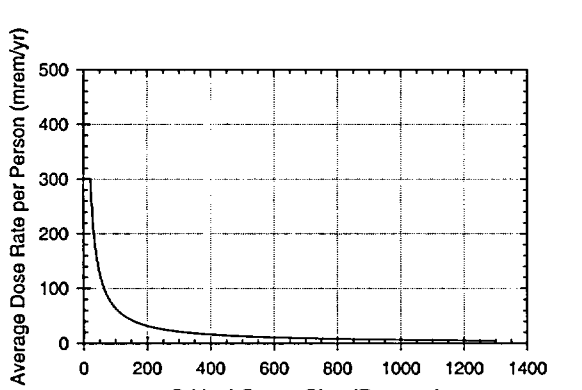

Figure 5-51. Average Dose Rate as Function of Critical Group Size for the Amargosa Valley, Estimated for the Expected-Value Base Case
The line indicates the average dose rate per person; the plateau value corresponds to the 300 mrem/year maximum dose rate calculated in the base case for the reference person. Approximately 20 people could incur this dose rate based on the calculated amount of radionuclides released to the biosphere and the average water usage per person in the Amargosa Valley. The distribution of these radionuclides among the entire population would reduce the dose rate to an average of approximately 5 mrem/year.

(i.e., the volume of water the radionuclides are dissolved into) could affect calculations of dose rates by possibly a factor of 70. It also sets approximate limits on how many people (20) can incur the maximum dose rate calculated for the base case for the assumed usage.

5.8.3 Sensitivity to Critical-Group Definition

The third sensitivity study examines the effect on calculated doses of the assumptions made for the base case regarding what constitutes the critical group. In the base case, radiation doses were calculated for a reference person based on an average resident of Amargosa Valley, using distributions for consumption of water and locally grown food taken from a survey of residents (Section 3.8.1). In this section the base case is compared with two other possible dose receptors. One alternative is a "subsistence farmer," who lives entirely on water taken from the maximally contaminated part of the contaminant plume, including all drinking water and all water used to grow produce and livestock. The other alternative is a "resident farmer," who is assumed to consume 50 percent locally grown food that is contaminated by water from the maximally contaminated part of the contaminant plume.

Figure 5-52 compares the two alternative dose calculations with the base case. The spread between the highest method (the subsistence farmer) and the lowest method (the base case) is a factor of 4 to 5. These results are consistent with the differences in these receptors types presented in Figure 3-80.

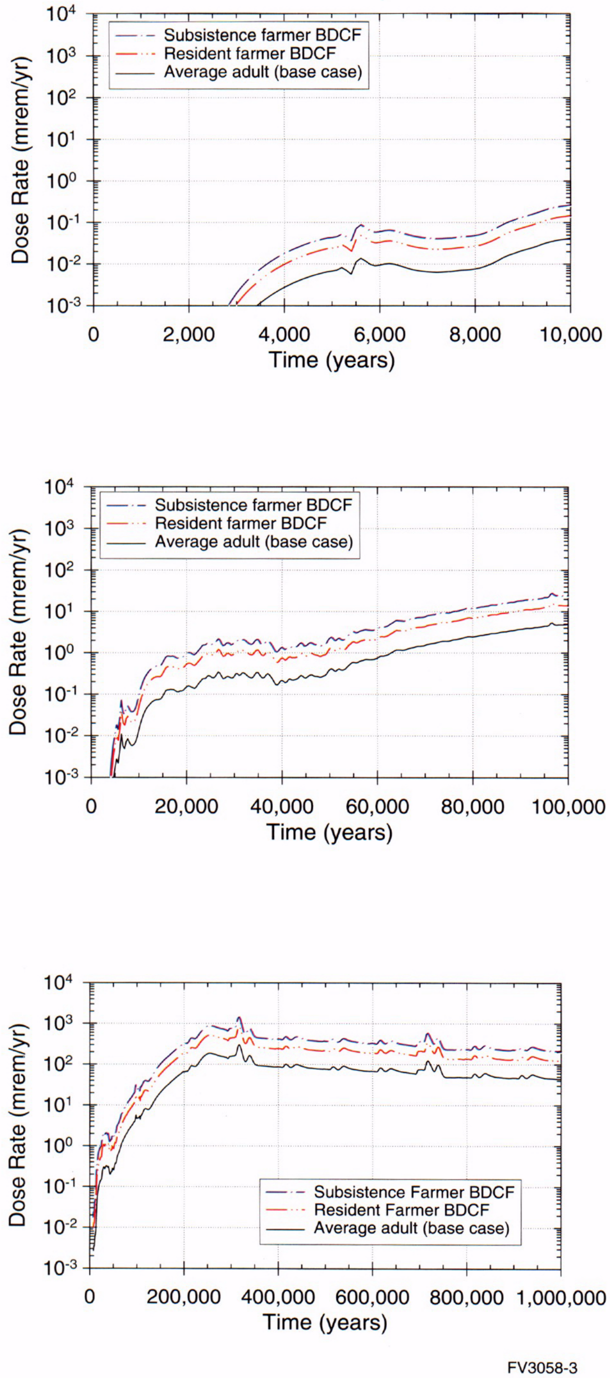

Figure 5-52. Total Dose-Rate History Curves for the Expected Value Base Case and for Two Sensitivity Cases in Which Different Critical Groups are Assumed

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6. SUMMARY AND CONCLUSIONS

The objective of the TSPA-VA was to conduct and document "a total system performance assessment based upon the design concept and the scientific data and analysis available by March 1998, describing the probable behavior of the repository in the Yucca Mountain geological setting relative to the overall system performance standards" (Public Law 104-206). This volume of the VA contains the information, analyses, and interpretations used to describe "probable" behavior of the proposed Yucca Mountain repository system.

The projected behavior of the Yucca Mountain repository system is based on the site-specific scientific data and analyses summarized in Volume 1, and in Section 3 of this volume. The Yucca Mountain repository and waste package design concepts used in this TSPA are described in detail in Volume 2, and the relevant scientific data and analyses used to evaluate the behavior of these designs are summarized in Section 3 of this volume. This information has been used to develop an estimate of the probable behavior of the repository disposal system, comprised of both engineered and natural components. The results of these analyses have been presented in Section 4 of this volume.

In examining and summarizing results describing the "probable" behavior of the Yucca Mountain repository system, it is important to understand that the evaluations are indicators of the postclosure performance impacts of the proposed repository. The analyses should not be construed as predictions in the normal sense of the word. Although an attempt has been made to incorporate the most current understanding of key processes affecting the long-term behavior of Yucca Mountain, such projections are uncertain. Although many of these uncertainties will still remain at the time of the License Application (LA), DOE will reduce the significant uncertainties sufficiently and modify the design as appropriate to provide NRC with reasonable assurance that post closure performance objectives can be met. The uncertainty is a result of several factors:

- The periods are long. The period for the quantitative analyses extends to 10,000 years and beyond. Over these long periods, there is uncertainty in the definition of likely future environments. This period is also long compared to available information about a number of principal factors affecting repository performance such as the degradation rates of corrosion-resistant metals.

- The site is heterogeneous. Water movement in the unsaturated and saturated zones at Yucca Mountain is expected to vary with location and with time because of the heterogeneous nature of the fractured rocks. Precisely defining the flow paths and volume and geochemical interactions along the flow paths is not possible.

- The system is coupled. Coupled interactions are expected to occur near the emplaced wastes. These interactions include thermal, chemical, hydrologic, and mechanical processes that can influence one another. For example, the chemical alteration of the rock caused by a temperature increase may cause the hydrologic properties of the rock to change. It is difficult to predict the magnitude and extent of these changes with any precision.

- Future populations are unknown. It is not possible to reasonably forecast changes in human activities. Therefore, the doses calculated are based on the activities of the present-day population in the region around Yucca Mountain. This assumption, which is consistent with internationally accepted recommendations (see Section 3.8), implies that the doses represent the range of likely performance of a repository for a hypothetical population.

Although these uncertainties are recognized in the analyses and interpretation of results, they do not detract from the goal of objectively evaluating how the system is likely to perform. To precisely identify the exact magnitude of the effects and consequences for disposing 70,000 metric tons of nuclear waste at Yucca Mountain is not expected by the regulators. For example, NRC has noted in 10 CFR Part 60.101 (a)(2):

> While these performance objectives and criteria are generally stated in unqualified terms, it is not expected that complete assurance that they will be met can be presented. A reasonable assurance, on the basis of the record before the Commission, that the objectives and criteria will be met is the general standard that is required. For 60.112, and other portions of this subpart that impose objectives and criteria for repository performance over long time periods into the future, there will inevitably be greater uncertainties. Proof of the future performance of engineered barrier systems and the geologic setting over time periods of many hundreds or many thousands of years is not to be had in the ordinary sense of the word. For such long-term objectives and criteria, what is required is reasonable assurance, making allowance for the time period, hazards, and uncertainties involved, that the outcome will be conformance with those objectives and criteria.

In addition, EPA has noted the following with respect to the degree of confidence that is expected (40 CFR 191):

> Performance assessments need not provide complete assurance that the requirements of 191.13(a) will be met. Because of the long period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames.

The assessment provided here is not final. It does not include the type of evaluation of a number of design options that will be conducted for the LA. Also, analyses to address design margin and defense in depth have not yet been completed. However, this assessment does include sufficient sensitivity and uncertainty analyses to illustrate the range of possible behaviors that might be anticipated. These analyses have assisted DOE in focusing the data-collection, model-validation, and design-development activities between now and the LA. While the projections of future behavior presented appear reasonable, additional information may be needed to demonstrate regulatory compliance in a licensing proceeding.

Although uncertainties exist regarding many factors affecting repository performance, these uncertainties have been reasonably bounded and analysis have been satisfactorily completed using these bounded values. Therefore some uncertainties and areas of limited data will remain as they are while other uncertainties may require further study in order to provide a sufficiently robust analysis of repository performance for the LA.

As noted above, it would be ideal to be able to make all decisions based on complete information. However, the behavior of the repository system over tens of millennia will never be known with certainty. The regulatory agencies agree that reasonable conclusions about whether a repository system can be expected to provide the public with adequate protection from nuclear waste need not include this degree of absolute certainty.

6.1 SCIENTIFIC DATA AND ANALYSES IN THE TOTAL SYSTEM PERFORMANCE ASSESSMENT FOR THE VIABILITY ASSESSMENT MODELS

One of the principal objectives of the analyses for this TSPA was to use all the available scientific data and analysis in the performance evaluation of the Yucca Mountain repository system. The data consist of a suite of laboratory, surface based, and in situ tests and observations conducted as part of the YMP. These tests and observations provided data that have been used in analytical tools consisting of conceptual, process, abstracted, and numerical models. These models, in conjunction with the test data for defining a range of parameter values, have been used as the basis for this TSPA.

An evaluation of total system performance is a projection or estimate of the expected future behavior of the repository system. With the possible exception of some naturally occurring uranium ore bodies and other natural analogs, there are no directly observable phenomena that are comparable to the potential repository system at Yucca Mountain. Because of this, it is necessary to extrapolate the projections of future behavior based on present-day observations of the same phenomena. The extrapolation of the relevant phenomena into the future is accomplished using models based on laboratory, surface based and in situ test data and observations. These models describe the behavior of the relevant processes.

Laboratory test data are valuable in improving confidence in models used for future projections of behavior because they can be conducted under well-controlled conditions and can be designed to address specific data needs.

Examples of laboratory testing that has been used in the development of models for this TSPA include:

- Corrosion testing of candidate waste package metals, including the outer corrosion allowance and the inner corrosion resistant barrier (Alloy 22)
- Intrinsic dissolution testing of the spent nuclear fuel and glass waste forms
- Alteration tests and secondary phase formation of spent nuclear fuel and glass
- Radionuclide mobility tests including solubility and colloid formation
- Radionuclide sorption tests
- Coupled thermal, mechanical, chemical, and hydrologic tests of rock alteration
- Rock matrix property tests to determine hydrologic properties

Surface based tests and observations are valuable in determining site-specific properties necessary to define how water moves through the unsaturated and saturated zones of the Yucca Mountain repository system. Surface based tests are conducted from a range of shallow (about 10 m, or 33 ft, deep) and deep (over 1,000 m, or 3,300 ft, deep) boreholes. The types of surface based tests and observations include:

- Mapping geologic features and hydrostratigraphy
- Mapping fracture characteristics and lithology
- Testing hydrologic properties
- Observing ambient water content and matrix potential in the unsaturated zone
- Measuring precipitation, temperature, and other meteorological variables
- Measuring moisture transients in the near surface (net infiltration)
- Measuring seismological disturbances
- Mapping and analyzing volcanic features
- Observing water potential in the saturated zone
- Observing ambient temperature and aqueous geochemistry
- Cross-hole testing of transport characteristics

In situ tests and observations are valuable in determining the site-specific properties necessary to define environmental conditions that control performance of the engineered barriers of the Yucca Mountain repository system. In situ tests and observations at Yucca Mountain have been made from a number of niches constructed in the Exploratory Studies Facility and other test facilities near Yucca Mountain, such as at Busted Butte. Although in situ tests are expensive because of the construction and operational costs of the underground facilities, they are the principal means of testing the host rock under conditions similar to what might be expected in the presence of a repository. Examples of in situ tests and observations include:

- Single and drift scale heater tests to evaluate the thermal, hydrologic, chemical, and mechanical response of the rock when heated

- Observations of in situ water content, chemistry, isotopes, and mechanical stress of the rock mass around the underground tunnels

- Tests of in situ hydrologic, geochemical, and transport properties of the rock mass

These observations and tests form the basis for a suite of process and numerical models that have been used to develop this TSPA analyses. Each of these models and their abstraction into the TSPA model are described in Section 3. The term "abstraction" is used to indicate the extracting of essential information. The TSPA models are usually referred to as abstracted models. Details of this abstraction are presented in the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i).

While these tests and observations form the scientific basis for the models used, it is important to acknowledge the uncertainty in these models. Part of this uncertainty is caused by the complexity of the individual processes and their interactions. Another component of the uncertainty is caused by the variability of the natural system and the inability to completely characterize this variability. To address the uncertainty in each of these process models, DOE has conducted a number of different expert elicitations. The results of these elicitations have provided this TSPA analyses with a reasonable range of expected parameters and models that extend the range beyond what might be determined solely by the test information.

6.2 PROBABLE BEHAVIOR OF THE REFERENCE DESIGN

The performance assessments provide a picture of the repository system evolution and probable behavior, where probable behavior is defined as the behavior specified by the base case. The assessment considers the potential for radionuclide release from the repository system and transport 20 km (12 miles) from the repository, where the radionuclides could be drawn in water from a hypothetical well. The assessment is made for the repository design concept under consideration as described in Volume 2. The behavior of other design concepts could be somewhat different. These analyses, including the sensitivity studies, provide a broad indication of the kind of behavior expected for the system, the probable behavior. This section briefly describes the design concept and discusses the probable behavior of the system.

The design concept for the Yucca Mountain repository system is to place the various waste forms, whether commercial spent nuclear fuel, defense high-level nuclear waste glass, or DOE-owned spent nuclear fuel, into large waste packages. These waste packages are made of an inner highly corrosion resistant nickel alloy (Alloy 22) and an outer layer of carbon steel. The waste packages are placed on supports within mined drifts located about 300 m (1000 ft) beneath the surface. Following emplacement of individual waste packages, the drifts are sealed to prevent access, but otherwise the facility will be designed to remain open for 100 years (and perhaps several hundred years) after the start of waste loading to allow maintenance and observation until a decision is made to permanently close the facility. This design forms the basis of this TSPA. The details of this design concept are presented in Volume 2.

The presentations in Sections 3 and 4 showed the probable behavior of the system from the viewpoint of a series of model results that, when integrated, yielded a description of the overall system behavior. This description was summarized in Section 2.4 as a series of time slices that synthesize the system response to the proposed design concept. These time slices were:

- Time of waste emplacement to time of repository closure
- Time of repository closure to several hundred years after closure
- Several hundred years to several thousand years after closure
- Several thousand years to ten thousand years after closure
- Ten thousand years to several tens of thousands of years after closure
- Several tens of thousands of years to one hundred thousand years after closure
- Several hundred thousand years to as long as a million years after closure

The assessment described in Section 4 indicates that the vast majority of radionuclides in the waste is immobile and never leaves the repository even if in contact with water. A small number of radionuclides, notably technetium-99, iodine-129, neptunium-237, and those radionuclides transported by colloids, are sufficiently mobile under some conditions that they could reach the biosphere downgradient from the repository. Therefore, these analyses indicate that the most important factors for system performance over time are the amount of water likely to contact the waste packages and the amount of waste exposed to that water. Consequently, long lived waste packages and engineered barriers or other factors that are effective in further limiting the contact of water with the waste will also be highly important to performance.

Under the base case scenario the quantities calculated to reach the biosphere are small: a negligible amount in 10,000 years and a dose rate for hundreds of thousands of years that is comparable to natural background activity. Although the assessment is conservative by virtue of overestimating the effects leading to release and transport, there are still some uncertainties in the estimates that will require further analysis. The sensitivity of the results to these uncertainties is discussed in Section 6.3.

6.3 SENSITIVITY ANALYSES OF THE REFERENCE DESIGN

One of the principal objectives of any total system performance assessment is to evaluate the significance of the assumptions made in defining the "probable" system behavior. One of the primary goals of this TSPA is to assist DOE in identifying, based on the reference repository design, the principal factors that affect the postclosure performance. A part of this objective is met by examining a range of possible outcomes predicated on a range of conceptual and parameter values. These results are presented in Sections 4.3 and 5. In addition, the possibility of some low-probability, potentially high-consequence disruptive scenarios has also been evaluated (Section 4.4). Finally, the effects of using different design options to compensate for some of the uncertainty in the various components of the natural and engineered system, and thus provide greater assurance of repository performance has been investigated (Section 4.5).

The sensitivity analyses conducted as part of this TSPA are summarized in this section. The summary includes a discussion of general insights gained during the course of the analyses. These insights include not only the direct quantitative sensitivity analyses, but also the understanding gained from a range of comparative analyses. Just as the individual results associated with a deterministic evaluation need to be tempered with realization of the uncertainty in the results, so too should the interpretation of a range of uncertainty analyses. For example, the importance of one component of the system can sometimes be masked by other, seemingly more significant components. It is also possible that the complete range of uncertainty for a particular component in the evaluation has not been fully evaluated. To address this issue, in some instances additional sensitivity analyses were conducted with wider uncertainty bounds. However, some judgment regarding the unquantified uncertainty must be used in assessing the overall significance of the principal factors in the repository safety strategy.

Finally, the significance of individual components at different locations and times must be examined because their importance can change depending on the performance measure used.

Evaluations of repository system performance are sensitive to different factors over different time frames. The analyses indicate no releases for the first several thousand years and the sensitivity studies indicate that this observation holds over a wide variety of variations of the components that could affect performance. The following summary addresses the sensitivities in the longer term. The summary has been broken into three time scales; up to 10,000 years, from 10,000 years to 100,000 years, and after 100,000 years.

6.3.1 Sensitivity Analyses over the First 10,000 Years

Over the first 10,000 years after waste emplacement, the overall performance is controlled principally by waste package failure. During this period, with few exceptions, the waste packages completely prevent water from contacting the wastes. A small fraction (on the order of 1/10 of 1 percent), of the waste packages may develop one or more small openings through the corrosion-resistant metal during the first 10,000 years. These packages would generally be located in areas of the repository either with a higher probability of more aggressive geochemical conditions or containing waste packages with a higher Alloy 22 corrosion rate. Because the reference design contains approximately 10,500 waste packages, some waste packages are anticipated to undergo more rapid degradation than others, simply because of the range in possible corrosion rates.

In addition to these "expected" failures, some low probability of failures may occur as a result of unanticipated events. These include:

- Waste packages that might fail prematurely by improper quality control of the welds or fabrication
- Impurities in the metals, leading to higher corrosion rates
- An unforeseen degradation mechanism acting on the waste package materials

Although procedures will be developed and implemented to minimize or eliminate these early failures, they have been included in this analyses in order to evaluate the sensitivity of the results to them.

Once the waste package has been breached, the next significant component is the amount of the waste form surface that is exposed and in contact with water. The amount of water entering the waste package is assumed to be proportional to the perforation area. For the commercial spent nuclear fuel and naval spent nuclear fuel, the negligible corrosion rate of the Zircaloy cladding minimizes the amount of exposed waste form surface. For the other waste forms, once the package is breached the entire surface area of the waste form is assumed to be exposed. In all of the TSPA-VA analyses, water is assumed to contact all of the exposed waste. This is a conservative assumption, but to do otherwise in a quantitative fashion would require a degree of sophistication that would be difficult to substantiate. For the highly soluble radionuclides that dominate the 10,000-year dose rates, the rate at which fuel is exposed and contacted by water dominates the release rate from the engineered barriers.

The calculated dose rate from radionuclides released from the waste package in this period is influenced by their travel time and by the degree of dilution that occurs as the radionuclides migrate to the biosphere. The travel time depends on the flow velocities in the unsaturated and saturated zones. The climate at Yucca Mountain is expected to change from the present-day dry conditions to a presumed wetter environment associated with what is believed to be the long-term average climate. The timing of this climate change and the net infiltration have a significant effect on the travel time of any dissolved radionuclides released from the engineered barriers in the first 10,000 years. Under present-day conditions, the time for 50 percent of the mass of highly soluble, unretarded species to travel from the repository to the water table is a few thousand years. It takes an additional few thousand years for 50 percent of the mass to travel in the saturated zone from the repository footprint to the assumed compliance point 20 km (12 miles) downgradient. Retarded species take significantly longer than these times. Therefore, if no releases occurred from the engineered barriers for thousands of years, then the present-day climate regime indicates that only a small fraction of the released inventory would be transported 20 km (12 miles) in the first 10,000 years. Invoking a climate change within the first 10,000 years significantly reduces these travel times. As the amount of water moving through the rocks increases, the velocity of the groundwater increases, causing a greater percentage of the groundwater to flow more rapidly through fractures in the nonwelded tuff units.

The effective amount of dilution as radionuclides move through the unsaturated and saturated rocks to the biosphere depends on several things. The dilution is influenced by the degree to which water contacting the waste is mixed with uncontaminated water in the emplacement drifts. It is also altered as the water bearing the radionuclides mixes with the water that has never entered the drift in the rock in and around the drifts, in the path to the water table, and in the paths through the saturated zone. Finally, the degree of dilution is affected by pumping at a well.

As noted in Section 4.1, the flux through the unsaturated zone within each of six different repository regions is assumed to mix the different sources of radionuclides created when each individual package is breached and begins to release radionuclides. In areas of the repository underlain by perched water bodies and/or significant lateral flow this is a reasonable assumption. At times when a significant number of waste packages have been breached and are releasing radionuclides this is also a reasonable assumption given the relatively close spacing of the waste packages. However, there is more uncertainty implicit in this assumption at early times (less than 10,000 years), when only a very few waste packages have been breached. If those breached packages are located in the southern half of the repository (where the flow is predominantly vertical), the degree of transverse mixing that might be anticipated between the breached waste package in the repository and the water table may not have been adequately captured in the model. Quantifying the effect of this uncertainty is not currently possible, given the degree of spatial averaging and numerical discretization used in the unsaturated zone radionuclide transport model. Although the significance of this uncertainty may be minimized by possible mixing in the saturated zone or at the well, it is anticipated that additional analyses will be required before licensing to define the significance of this issue.

In summary, the most significant components in the determination of the dose rates at 20 km (12 miles) from the Yucca Mountain repository over the first 10,000 years are the following:

- Seepage contacting the waste packages and waste forms
- Waste package containment, including effects both of premature waste package failures and of waste package degradation rates
- Rate of cladding failure
- Chemistry of water contacting waste package surfaces
- Travel time, including the effect of timing and the magnitude of climate change
- Degree of mixing in the unsaturated and saturated zones
- Biosphere dose conversion factor

The peak dose rates during this period are forecast to be small. The median (50th percentile) dose is 0.002 mrem/year with the 5th and 95th percentiles of 0 and 0.8 mrem/year, respectively. The mean peak dose rate is forecast to be 0.1 mrem/year. The variations in the forecasted dose results primarily in variations in the first two components. Finally, it should be noted that, in the event of immediate cladding failure, Figure 5-29 indicates that the median dose could be about 1 mrem/year in the 10,000 year time frame.

6.3.2 Sensitivity Analyses from 10,000 to 100,000 Years

It is expected that the potential future regulatory requirements for Yucca Mountain will focus on dose assessments to 10,000 years. However, analyses beyond 10,000 years will be conducted to gain additional insights into repository system behavior. It is likely that the goal of the analyses beyond 10,000 years will be determining the average behavior and its confidence interval. This is different than examining the full range of potential performance (as has been done in Sections 4.3 and 5) that has been used as the basis for defining the significance of the principal factors of the repository safety strategy. Therefore, although useful insights into factors affecting dose rates beyond 10,000 years are discussed below, the degree to which these uncertainties need to be addressed before licensing requires consideration of how these long-term projections will be used in the LA.

From 10,000 to 100,000 years after the repository is closed, the important factors controlling the dose rate at 20 km (12 miles) change from those that were important in the first 10,000 years. The principal reason is the change in the radionuclides that dominate the dose rate. As the period is extended, the controlling radionuclides generally (but not always) change from being the highly soluble, unretarded radionuclides such as technetium-99 and iodine-129 to low solubility, slightly retarded species dominated by neptunium-237. Even at extended times the high solubility radionuclides may dominate the predicted dose rate if any of the following conditions are present:

- The rate of waste package failures is low.
- The amount of seepage into the drifts or into the waste packages is low.
- The solubility of the solubility-limited radionuclides is low.

An additional explanation for the change in key components as the period of interest is extended beyond 10,000 years is the difference caused by the groundwater flow regime. While the advective travel time can make a difference when considering the present-day climate over 10,000 years, over a longer period the nonsorbed or poorly sorbed radionuclides that are released from the engineered barriers will reach the hypothetical well located 20 km (12 miles) downgradient. However, once the climate state switches to being the long-term average precipitation, the net infiltration, percolation flux, and advective velocity all increase significantly. This decreases the travel time for any radionuclides that may be traveling through the unsaturated or saturated zones. Even over this period, the more highly sorbed radionuclides are effectively immobile in the Yucca Mountain environment.

The dominance of specific radionuclides in the dose rate changes over the 100,000-year period. For example in the expected value base case realization presented in Section 4.2, the time at which neptunium-237 begins to dominate the dose occurs about 40,000 years after repository closure. Because of this change, the significant components driving the performance are some combination of those that affect the concentration and dose rate of technetium-99 and those that affect the concentration and dose rate of neptunium-237. The controlling factors are examined separately in the following paragraphs.

High solubility, low retardation radionuclides such as technetium-99 are generally called "release-rate-limited" radionuclides. The release rate from the engineered barriers is controlled by the rates of waste package failure, the surface of the waste form exposed through clad failures and contact with water. The rate of waste package failure is a function of the presence or absence of seeps and the degradation rate of the Alloy 22 metal in the waste package. If the clad is failed and water contacts the waste, the advective or diffusive travel times through the engineered barriers are generally short in comparison to the 100,000-year period of the analyses. This short travel time is, in part, a result of the conservative assumption that the water pathways inside the waste package and the water film along the waste form surface are continuous. Therefore, the advective and diffusive travel times are short for the highly soluble radionuclides released from the engineered system after the waste packages have been breached.

After the low-retardation radionuclides are released from the engineered barriers, their travel times to the 20-kilometer (12-mile) hypothetical well are on the order of several thousand years for the present-day climate. This delay time is reduced if there is a change to a wetter climate. In addition to the delay, the radionuclides released from the engineered barriers are diluted as the water containing the dissolved radionuclides mixes and disperses through both the unsaturated and saturated zones. Because not all the water that enters the drift has entered waste packages, some has diverted around the waste package, this mixing starts as soon as the water containing the dissolved radionuclides leaves the waste package and enters the drift. Because not all the water that intersects the drift has entered the drift, some has diverted around the drift, the mixing continues as the water containing dissolved radionuclides leaves the drift and enters the rock. This mixing effectively reduces the concentrations of the dissolved radionuclides.

The release rate of the less mobile radionuclides such as neptunium-237 is controlled by their solubility in the water. For these radionuclides, the solubility of the radionuclide in the water film on the waste form surface and the advective flux of water over the waste form surface control the release rate from the engineered barriers. For any repository region, the mass release rate for the solubility-limited radionuclides is a function of the cumulative number of waste packages that have been breached and the amount of water that seeps into each waste package. These aspects of the system are, in turn, controlled by the fraction of the waste packages in contact with seepage water, the amount of water that seeps, and the Alloy 22 degradation rate. This fact has been reinforced by the identification of the key parameters in the multiple-realization analyses presented in Section 4.3.

The solubility of some radionuclides, including neptunium, in the water on the waste form surface can be significantly affected by geochemical reactions of that water with the waste form as it alters. Spent fuel may progress through a complex series of alteration states. The different altered forms of the spent nuclear fuel can have neptunium retained in the solid state rather than being released to the aqueous phase. If neptunium is contained within these alteration products, then it will be immobile until the secondary and tertiary alteration phases have dissolved. The effect of these alteration phases on limiting the neptunium-237 dose has been investigated in Section 5.5.

Because the solubility limit is applied separately to each waste package, the total inventory exposed and in contact with water does not make an appreciable difference in the release rate of neptunium-237 from the repository. In part this is caused by the model not explicitly linking the solubility constraints to the clad failure model. Neptunium release remains almost unaffected by cladding degradation until the inventory in the initially breached waste packages has been depleted. With a 2 million year half-life, neptunium-237 does not significantly decay during the period of the analyses. The depletion time is a function of the amount of water that enters each waste package and the percent of the cladding that has been degraded (for commercial spent nuclear fuel). The analyses presented in Section 4.2 and 5.5 show that this time is several hundred thousand years.

Once the solubility-limited radionuclides are released from the waste package and transported through the invert, their transport through the unsaturated tuffs is controlled by the retardation characteristics of the rock. Many solubility-limited radionuclides are very highly sorbed on tuffs (they are essentially immobile in the Yucca Mountain setting). Neptunium-237 is slightly retarded on the tuffaceous rocks within the unsaturated zone. Therefore, in the time periods of interest, neptunium-237 released from the repository will travel through an average of 300 m (1,000 ft) of unsaturated tuffs to the water table. During the long-term climate state, this distance would be reduced to 220 m (720 ft) due to an assumed 80-meter (260-ft) rise of the water table. Eventually, these radionuclides will be transported through the saturated zone to the hypothetical well located 20 km (12 miles) downgradient from the repository.

Another factor that could have an impact on overall performance is the colloidal transport of plutonium. There is significant uncertainty about the nature, stability, filtration, and adsorption and desorption characteristics of naturally occurring and waste form generated colloids. For the anticipated range in colloid properties considered, the dose rate attributed to colloidal plutonium-242 and plutonium-239 is less than the dose rate caused by neptunium-237. However, either expanding the possible range in colloid properties or reducing the neptunium solubility may cause colloidally transported plutonium-242 to be the dominant dose contributor at times in excess of 100,000 years.

In summary, the most significant components in determining the dose rates at 20 km (12 miles) from the Yucca Mountain repository over the first 100,000 years are the following:

- Fraction of waste packages with seepage
- Waste package degradation rate
- Cladding degradation rate
- Dilution and mixing in the unsaturated and saturated zones
- Timing and magnitude of climate changes
- Formation and transport of radionuclide-bearing colloids
- Formation of secondary neptunium mineral phases (related to waste form degradation rate)
- Neptunium solubility (related to the alteration rate of spent nuclear fuel)
- Biosphere dose conversion factor

The median (50th percentile) peak dose rate during this period is forecast to be 0.09 mrem/year, with the 5th and 95th percentiles at 0.0 and 200 mrem/year, respectively. The mean peak dose rate is forecast to be 30 mrem/year.

6.3.3 Sensitivity Analyses for Times Greater than 100,000 Years

At times longer than 100,000 years, neptunium-237 is again the dominant radionuclide. As time proceeds, several events occur:

- The number of degraded waste packages (with at least one opening through Alloy 22 inner barrier) continues to increase
- The amount of degradation (the extent of the openings) through each waste package continues to increase
- The amount of seepage that enters each degraded waste package continues to increase
- The fraction of the waste form surface area exposed (because of cladding degradation) and in contact with water continues to increase

All of these factors tend to cause the release of neptunium-237 from the waste packages to continue to increase with time. This continued increase is illustrated in the base case deterministic results described in Section 4.2. As the releases from the engineered barriers increase with time, the concentrations and dose rates downgradient from the repository increase accordingly.

Eventually the neptunium-237 inventory will be depleted from the degraded waste packages. The length of time for depletion to occur is a function of the neptunium-237 inventory as well as the factors listed in the previous paragraph. For the base case deterministic analyses, this period is several hundred thousand years. After this time, the release rate from the engineered barriers for neptunium-237 decreases, as do the corresponding concentrations and, ultimately, dose rates.

Because the release rate depends on the seepage amount and fraction of waste packages contacting seepage water, climate affects release from the engineered barriers. In particular, during the superpluvial climate, the presumed increase in net infiltration causes an increase in percolation and, therefore, seepage. As a result, at the time of the superpluvial climate, which is assumed to be several hundred thousand years from the present, the dose rate could increase. Although this increase is in part an artifact of the presumed instantaneous change in the climatic regime from the long-term average to the superpluvial climate, some increase would be expected when the seepage increases.

As noted in the discussion of the 100,000-year sensitivity analyses, the travel time of the nonsorbed and partially sorbed radionuclides from the repository to the water table and then to the 20 km (12 mile) hypothetical well is short compared to the overall period of the analyses. However, some dilution occurs when the water containing dissolved radionuclides is released from the engineered barriers and mixes with the moving groundwater in the rock. Although not considered in the base case analyses, additional dilution could occur if the hypothetical well pumps more water than contained within the maximally contaminated zones of the aquifer.

In summary, the most significant components in determining the dose rates at 20 km (12 miles) from the Yucca Mountain repository over the first million years are the following:

- Fraction of waste packages contacting seepage water
- Waste package degradation rates
- Cumulative amount of degraded cladding
- Dilution in the unsaturated and saturated zones
- Biosphere dose conversion factors

The median peak dose rate calculated in this period is 8 mrem/year. The 5th and 95th percentiles are 0.07 and 1000 mrem/year, respectively. The mean peak dose rate is forecast to be 200 mrem/year.

6.4 PRINCIPAL FACTORS AFFECTING POSTCLOSURE PERFORMANCE

The principal factors affecting the repository system are those factors that bear directly or indirectly on one or more of the components identified in the sensitivity studies as being potentially important to performance. These factors are summarized in Table 6-1. They are grouped according to the system attributes of the *Repository Safety Strategy* (DOE 1998).

The major insights gained from the sensitivity analyses for the reference design are summarized in Section 6.3. These results have been interpreted to guide the definition of the information required to enhance confidence in the performance-assessment analyses for the LA. Each of the principal factors affecting postclosure performance was examined to determine whether that factor has a high, medium, or low contribution to the overall system performance.

The significance of the uncertainty in the principal factors on the assessment of the postclosure system performance may be identified in several different ways. One method is to examine the multiple realization performance analyses and their corresponding regression analyses presented in Section 4.3 to identify which parameters within the TSPA-VA base case simulations are most significant. This is an appropriate technique and provides very useful insights into what is driving the system behavior, but is predicated on the degree of uncertainty included in the base case models and parameters. However, it is possible that a few very uncertain parameters will mask the potential contribution to the uncertainty of other parameters. Therefore, this method can not be used in isolation or without examining the contribution of the other parameters to the system performance.

In order to examine the significance of alternative models and to examine more explicitly the role that some parameters may have in the system performance, a range of comparative analyses have been presented for each of the TSPA-VA model components in Chapter 5. These comparative analyses include sampling the uncertain parameter at

Table 6-1. Significance of Uncertainty in Principal Factors on Post Closure System Performance - Summary of Sensitivity Analysis for Viability Assessment Reference Design

Key Attribute of the Repository Safety Strategy	TSPA Model Components	Principal Factor for the Repository Safety Strategy	Significance of Uncertainty in TSPA[1] Performance Period (years) 10k	100k	1M	Reference Figure Location Base Case	Alternative Models
Limited water contacting waste packages	Unsaturated Zone Flow	Precipitation and infiltration into the mountain	L	M	L	5-5	5-1, 5-2, 5-3
		Percolation to depth	L	L	L	5-5	5-6, 5-7
		Seepage into drifts	H	H	H	4-34, 5-8	NA
	Thermal Hydrology	Effects of heat and excavation on flow (mountain-scale)	NA	NA	NA	NA	NA
		Effects of heat and excavation on flow (drift-scale)	L	M	L	NA	5-9, 5-10
		Dripping onto waste package	L	L	L	NA	5-18
		Humidity and temperature at the waste packages	L	L	L	NA	5-11
Long waste package lifetime	Near-Field Geochemical Environment	Chemistry of water on waste package	H	L	L	NA	5-14, 5-22
	Waste Package Degradation	Integrity of the outer carbon steel waste package barrier	NA	NA	NA	NA	NA
		Integrity of the inner corrosion-resistant waste package barrier	H	H	M	4-34, 5-16	NA
Low rate of release of radio-nuclides from breached waste packages	Waste Form Alteration and Mobilization	Seepage into waste packages	L	L	L	5-26	5-27
		Integrity of spent nuclear fuel cladding	H	M	M	5-28	5-29, 5-30, 5-31
		Neptunium solubility	L	M	L	5-32	5-33
		Dissolution of uranium oxide and glass waste forms	L	M	L	4-40, 5-35	NA
		Formation and transport of radionuclide-bearing colloids	L	M	L	5-36	NA
		Transport through and out of the engineered barrier system (including waste packages)	L	L	L	5-37	5-38
Radionuclide concentration transport from the waste packages	Unsaturated Zone Transport	Transport through the unsaturated zone	L	L	L	5-42	5-41, 5-43, 5-44, 5-45
	Saturated Zone Flow and Transport	Flow and transport in the saturated zone	M	M	M	4-34, 4-40	5-47, 5-48, 5-49
		Dilution from pumping	H	H	H	NA	5-51
	Biosphere Transport	Biosphere transport and uptake	M	M	M	4-34, 5-50	5-52

[1]H —High Significance (Uncertainty in principal factor, or its absence, results in a factor over 50 increase or decrease in peak dose rate from the "expected" value)
M—Medium Significance (Uncertainty in principal factor, or its absence, results in a factor of 5 to 50 increase or decrease in peak dose rate from the "expected" value)
L—Low Significance (Uncertainty in principal factor, or its absence, results in a factor less than 5 increase or decrease in peak dose rate from the "expected" value)

discrete probabilities (principally the 5th and 95th percentiles of the distribution as well as the mean of the distribution for comparison to the expected-value realization described in Section 4.2). The results of these analyses confirmed the significance of the parameters identified in the regression analyses described in Section 4.3 and also provided a method to rank the relative contribution of each of the principal factors.

The ranking of the significance of the principal factors presented in Table 6-1 has therefore been based on both the multiple realization regression analyses and the one-off comparative analyses. Where both methods indicated the same high significance, the decision to label that factor as having a high significance was straightforward. Where the two methods gave differing results or, more commonly, where the significance based on multiple realizations was masked by more significant factors, the factor was assigned the significance based on the comparative analyses. In some cases the comparative analyses included alternative conceptual models which, if true, could lead to substantially improved or degraded performance. The results of calculations using these alternative representations (presented in Chapter 5) were also used to adjust the rankings, as appropriate. This was done to ensure that the assessment of the significance of the each principal factor is reasonably complete, is defensible and that it accommodates the full breadth of current understanding as well as the factor's potential effect on postclosure performance.

The analyses of significance have been conducted over different time scales to reflect that the behavior of the system changes with time as does the significance of the principal factors of the repository safety strategy.

Table 6-1 focuses on the principal factors affecting the expected or probable repository postclosure performance. Other factors relating to potentially disruptive processes and events have been described in Section 4.4. These consequence analyses, when combined with the understanding of the probabilities of these disruptive scenarios occurring, implies that the long-term risks to public health and safety associated with these scenarios are minimal. Therefore, the uncertainties in these processes and events (seismicity, volcanism, nuclear criticality, and human intrusion) are deemed to have a low significance on overall performance.

An evaluation of significance requires combining both objective and subjective assessments of appropriate information. To provide objective evidence of significance, a range of sensitivity analyses have been performed. These sensitivity analyses have been used to define significance with respect to the magnitude of the effect of the uncertain parameter or model on the dose rate at a hypothetical well located 20 km (12 miles) downgradient from the repository. This section reports the results of those analyses in terms of "high," "medium," or "low" sensitivity to uncertainty. For the assessment of uncertainty given in this section and in Table 6-1, the following definitions were used to assign a ranking of high, medium or low. To rate a particular factor as having high significance on dose rate, varying the range between the mean and the 95th percentile of that parameter causes a change of over 50 times in the dose rate. In addition, if the absence of such a factor could result in a change in the projected dose of a factor of over 50, it also would be deemed to have a high significance. A medium significance corresponds to a change of 5 to 50 times the dose rate and a low significance indicates a change of less than 5 times the dose rate. These criteria were applied over the range of time periods of concern: 10,000 years, 10,000 to 100,000 years, and 100,000 to 1 million years.

Objective measures of significance are useful, but they presuppose that the uncertainty in the parameter or model is well characterized. One source of uncertainty may arise from the fact that not all possible alternative conceptual models have been considered. Also, the models themselves may have inaccuracies that are not captured in the analyses. For example, a parameter may impact the results significantly over a certain range of values, but outside that range the results are insensitive to the value of that parameter. If the parameter range does not extend into the significance range, then the analyst may falsely conclude that the parameter is not important. Therefore, judgment must be used to assign significance to a particular parameter or model because a range and synergistic effects that may not have been fully evaluated in the sensitivity analyses can be an exercise in judgment. The determinations of significance in the following paragraphs have been based on objective criteria. However, the influence of judgment in modifying the significance ratings for each of principle factors is given in Section 2.2-1 of Volume 4. The changes in the values that have resulted from the incorporation of judgment are shown in Volume 4, Table 2-2.

6.4.1 Precipitation and Infiltration of Water into the Mountain

The amount of water that enters the unsaturated zone at the surface controls the amount of water that percolates to depth and, ultimately, the amount and location of seeps into the repository drifts. Generally, the lower the infiltration, the less seepage into the drifts and the less water that can contact the waste package and the waste form. Therefore, the time and location variability in precipitation and infiltration are significant factors in overall system performance. The significance of this principal factor is estimated to be higher in the period from 10,000 to 100,000 years because the solubility-limited radionuclides control the dose rate in this period. The release of these radionuclides from the engineered barriers is, in large part, a function of the volumetric flow rate into the drifts and into the waste packages. The net infiltration has a moderate significance on the projected dose rate based on variation in the range of plausible infiltration rates (Section 5.1).

6.4.2 Percolation to Depth

Percolation flux is closely correlated with net infiltration. The uncertainty in percolation flux is directly related to the uncertainty in net infiltration. Percolation flux controls the fraction of the repository with seeps and the seepage amount. Therefore, percolation is likely to have an effect similar to infiltration on the dose rate. However, the base case analyses only showed a low significance of this factor, based on the fracture flow properties, which was the only parameter related to percolation varied in this set of analyses (Section 5.1).

6.4.3 Seepage into Drifts

Seepage into the drifts is a significant factor for many reasons. Seepage controls waste package degradation because Alloy 22 only corrodes in the presence of liquid water. Following the creation of openings through the Alloy 22, the seepage volume controls the amount of water that can enter the waste package and dissolve the waste form. The flux of water into and through the waste package in turn controls the release rate of the solubility-limited radionuclides from the waste package. The high significance of seepage at all time periods can be ascertained from the Monte Carlo analyses presented in Section 4.3 (where seepage fraction or seepage amount were consistently in the top four of the most significant variables) and in Section 5.1.

6.4.4 Effects of Heat and Excavation on Flow (Drift Scale)

Heat can drive water away from the emplacement drifts and enhance flow because of condensation and refluxing in the earliest time period. Therefore the heat can modify waste package corrosion rates and other aspects important to performance. However, the effects of heat are shown to only have a low impact on repository performance in the period up to 10,000 years. In the later period, the heat will have diminished and its direct impact on the redistribution of flow will also be minor. However, heat can cause permanent effects on the flow system. For example, the heat can modify flow properties by altering minerals in fractures and creating mineral caps above the heated area, similar to those observed at geothermal sites. Likewise, excavation can alter the flow properties, increasing bulk permeabilities near the drifts. These alterations have been approximated by changing the fracture properties contained in the seepage sensitivity analyses described in Section 5.1. This aspect of altering properties of the host rock leads to an assessment of moderate importance to performance in the middle time period, as illustrated in the sensitivity analyses described in Section 5.1.

6.4.5 Dripping onto Waste Packages

In the current analyses, any seep located half way up the drift wall is conservatively assumed to directly hit the waste package. However, many seeps may simply form a film around the drift wall or fall on rubble around the waste package and not directly intercept the waste package. This diversion of water may be significant, but is believed to be less significant than the presence of the seep itself. Variations in the surface area of the waste package that becomes wetted show this factor to be of low significance to performance.

6.4.6 Humidity and Temperature Effects on Waste Packages

Corrosion of the carbon steel layer on the outside of the waste package can be initiated and sustained at values for relative humidity greater than about 70 percent and temperatures less than about 100°C (212°F). Although most of the waste package performance is caused by the very slow corrosion rates of the Alloy 22 inner barrier of the waste package, during earlier periods (less than 10,000 years) the outer barrier does provide some protection. However, the overall significance of this factor is shown to be low during all time periods (Section 5.2).

6.4.7 Chemistry Effects on Waste Packages

The chemistry of the water on the waste package surface can significantly affect the degradation rate of both the carbon steel material of the outer waste package and the inner corrosion-resistant layer. As noted in Section 3.4, the degradation rate of Alloy 22 under benign water compositions is less than the degradation rate under more aggressive chemical conditions. The presence of microbes also changes the chemistry, and thus the corrosion rates. In addition, the chemistry of the water can affect both the degradation rate of the waste form and the solubility of neptunium-237. This factor, therefore, has a high impact on performance during the first 10,000 years when water is modified as it travels through the concrete liner, but drops to low significance at later times (Sections 5.3 and 5.4).

6.4.8 Integrity of Inner Waste Package Barrier

In the reference design, the corrosion degradation rate of the Alloy 22 corrosion-resistant alloy is seen as one of the dominant factors affecting the postclosure performance. The effect is illustrated in the regression analyses presented in Section 4.3 and the comparative analyses presented in Section 5.4. Not only does the degradation control the time at which the initial opening is formed through each waste package, but it also affects the number of openings generated through each waste package. The number of openings significantly affects the amount of seepage that can enter each waste package, which in turn controls the advective release of solubility-limited radionuclides, notably neptunium-237, from the waste package. This factor has a high significance over all but the longest time frames in the analyses of reference design postclosure performance, as documented in Section 5.4.

6.4.9 Seepage into Waste Packages

After the waste package has failed because of at least one opening through the corrosion-resistant inner container, the amount of water that enters the waste package controls the advective release of solubility-limited radionuclides. However, changing the percentage of waste packages wetted and changing the resulting flux through the waste package only showed a small change in dose rates, resulting in an assignment of low for significance (Section 4.2).

6.4.10 Integrity of Spent Fuel Cladding

The degree of degradation of the cladding significantly affects the amount of the inventory potentially exposed to liquid water. The dose rates of the high-solubility radionuclides, such as technetium-99, depend on the fraction of exposed inventory. Because the dose rates during earlier periods are controlled by the high-solubility radionuclides, the significance of cladding is greater at early times. The significance of cladding is high for the first 10,000 years and relatively less significant, but still of moderate importance at late times.

6.4.11 Dissolution of UO_2 and Glass Waste Form (Waste Form Integrity)

The alteration rate of the different waste forms is relatively rapid (thousands of years) compared to the period of interest (tens to hundreds of thousands of years). Therefore, the dissolution rate is not a significant factor in the overall dose evaluation at early times. Before 50,000 years technetium is the most important contributor to dose, after that time neptunium becomes the dominant contributor. However, the possibility that secondary phases are created at the spent nuclear fuel can effectively reduce the mobile concentration of neptunium-237. Therefore, this factor has the potential to be moderately important in the period between 10,000 and 100,000 years. After the secondary phases have been dissolved, the effect is mitigated, resulting in a reduction of the significance at times greater than 100,000 years.

6.4.12 Solubility of Neptunium-237

Neptunium solubility is a moderately significant contributor to the long-term dose assessment. The contribution of neptunium-237 is less significant at earlier times when the doses are primarily attributed to more mobile radionuclides such as technetium. However, at times greater than several tens of thousands of years, or in cases where the seepage flux is high, neptunium solubility can be a significant factor in postclosure performance projections. The solubility of the secondary phases of the fuel/glass is also important, because it may lead to a delay or reduction in the overall release of neptunium at times less than 100,000 years.

6.4.13 Formation of Radionuclide-Bearing Colloids

Plutonium colloids are responsible for the peak dose in a significant number of the TSPA-VA realizations during later times. It is one of the more significant findings in TSPA-VA that, under certain conditions, colloid-facilitated transport is moderately important to performance in the time period from 10,000 to 100,000 years.

6.4.14 Transport Within and out of the Engineered Barrier System

In the current TSPA analyses, if water gets into the waste package it was conservatively assumed to contact the entire exposed waste form surface. No credit is taken for the fact that a drip entering the waste package at one opening has a low likelihood of encountering the waste form at the other end of the waste package. In addition, the time it may take radionuclides to diffuse along a thin water film layer within the waste package was not considered. Quantifying the effects of these conservative assumptions is difficult. Therefore, the transport of radionuclides through the engineered system elements beneath the waste package (sorption in the invert) for any time period was shown to be of only low significance to performance.

6.4.15 Transport Through the Unsaturated Zone

Based on the current unsaturated zone flow model, the advective travel time through the unsaturated zone depends on the percolation flux distribution that is in turn controlled by the climatic conditions. Under the current dry climate, the unsaturated zone may provide a significant barrier to the migration of highly and slightly sorbed radionuclides. Under climate states with higher percolation flux, only the highly sorbed radionuclides are still retained in the unsaturated zone. Therefore, the significance of this barrier to release to the saturated zone may change with time as the climate state varies. In addition to the transport time, the unsaturated zone dilutes the concentration of the radionuclides released from the engineered barriers. The effects of unsaturated zone transport were investigated by changing sorption coefficients, assigning a value of zero for matrix diffusion, and assigning zero for sorption coefficient of the actinides (Section 5.6). However, the range investigated for these parameters only showed this factor to be of low significance at all periods.

6.4.16 Transport in the Saturated Zone

The time it takes for radionuclides to advectively travel through the saturated zone to a distance of 20 km (12 miles) is a significant fraction of the period of interest for 10,000 years. This is especially true for those radionuclides sorbed on the alluvial sediments. For longer periods and during climate regimes characterized by the long-term average climate, travel times in the saturated zone may not provide as much of a barrier to radionuclide migration. The saturated zone also provides some dilution of those radionuclides released from the unsaturated zone. The TSPA-VA sensitivity analyses of the saturated zone flow and transport has a moderate significance relative to other factors (as noted in Sections 4.3 and 5.7) for the three time periods.

6.4.17 Dilution from Pumping

If the volume of water extracted in the hypothetical well is significantly greater than the volume of water within an individual stream tube in the saturated zone, then significant dilution can occur at the well head. The effect of this dilution would diminish as the natural dilution in the saturated zone is increased. No credit is taken for the pumping dilution in the base case analyses of the reference design. The significance of this dilution depends on the size of the pumping well and the magnitude of the natural dilution in the saturated zone. Depending upon the assumptions concerning the amount of water pumped, the dilution factors investigated showed, at all times, a high significance in changing the dose to the average members of the critical population (Section 5.8).

6.4.18 Biosphere Uptake

After water containing dissolved radionuclides is extracted from the hypothetical well, the projected dose rate is a function of the range of possible water uses and food consumption habits of the exposed population. Although there is a linear relationship between the dose conversion factor and the dose rate (for a given radionuclide concentration at the well head), the changes in the dose rates show this factor to be of moderate importance in all time periods. (Sections 4.3 and 5.8).

6.5 IMPROVING CONFIDENCE IN THE TOTAL SYSTEM PERFORMANCE ASSESSMENT FOR THE LICENSE APPLICATION

The data and analyses summarized in Section 6.1-6.4 of this volume comprise a portion of the information needed to construct a complete postclosure repository safety case. In order to provide reasonable assurance that a repository at the Yucca Mountain site will not result in a significant long-term risk to public health or safety, the postclosure safety case must include:

- Explicit evaluation of expected repository performance

- Analyses of the degree of design margin and defense in depth that could improve performance and mitigate uncertainties in performance

- Explicit consideration of processes and events that, if present, have the potential to disrupt the repository system

- Supporting information regarding long-term behavior from natural and man-made analogs

- Plans for long-term testing and monitoring of the repository system

The purpose of the TSPA-VA described in this volume has been to examine the current understanding related to the first and third elements of the safety case, that is, the expected repository performance and the process and events that, if present, have the potential to disrupt the expected repository performance. The probable performance has been described in the context of how the four elements of the repository safety strategy work in concert to first minimize the contact of water with the waste and then reduce the concentration of any radionuclides that are released from the engineered barriers.

Based on the results of the TSPA analyses presented and discussed in this volume, areas of potential improvements in the analyses can be identified. Possible model enhancements and analyses that have the potential for improving the confidence in the TSPA for the site recommendation and LA are provided in Section 6.5.1. In addition, many important observations and insights have also been provided by independent groups, most notably by the TSPA Peer Review Panel and NRC. These comments are discussed in Sections 6.5.2 and 6.5.3, respectively. Section 6.5.4 provides some concluding remarks.

6.5.1 Assessment of Potential Activities to Increase the Confidence in the Total System Performance Assessment Based on the Results of the Total System Performance Assessment for the Viability Assessment

For each of the principal factors associated with the TSPA model components, the potential significance of some of aspects of model uncertainty has not been investigated in the TSPA-VA. This is in part a function of the objective of focussing the analyses on the probable behavior of the repository system which implies evaluating the expected performance as opposed to the performance associated with all the possible alternative hypotheses and models. The sensitivity analyses presented in Section 4.3 and Chapter 5 provide an indication of the possible range of performance, but can not be construed as being exhaustive. It is expected that the TSPA analyses developed for the site recommendation and LA will address these remaining uncertainties. The following paragraphs present possible model enhancements and analyses that have the potential for improving the confidence in the future assessments of repository performance.

6.5.1.1 Precipitation and Infiltration into the Mountain: Unsaturated Zone Flow

- *Abruptness of transition of climate changes.* The relation between the magnitude of the dose-rate "spikes" and the time of transition from one climate to another is not known. It is possible that noninstantaneous transitions would lead to lower peak dose rates.

- *Climate analogs.* The current approach is to base infiltration modeling on appropriate climate analogs (i.e., places that currently have climate conditions like those expected at Yucca Mountain for the future climate). The approach could be improved by taking temperature and other factors into account in addition to precipitation when defining the analogs.

- *Timing and duration of climate states.* The current model, using three distinct climate states, is simplistic and without a strong basis. Developing a more defensible basis for the number, timing, and duration of climate states could enhance confidence in the model.

- *Infiltration uncertainty.* A more quantitative basis for the uncertainty distribution for net infiltration (i.e., the probabilities in Table 3-5) could be obtained by running the infiltration model in a probabilistic mode (e.g., using Monte Carlo simulation, which is described in Section 4.3) to derive the infiltration uncertainty from the uncertainties in the model input parameters.

- *Infiltration for future climates.* Estimates of infiltration for future climates could be improved by explicit inclusion of processes that should be different for future climates, including effects of temperature, cloudiness, vegetation type, surface water runoff/run-on, and snow cover. Even for current conditions, some experts in the unsaturated zone flow model expert elicitation (CRWMS M&O 1997o) suggested that runoff and run-on might be more important than is assumed in the current infiltration model.

- *Model testing.* Confidence in the infiltration model could be enhanced by testing it using analogs with better-known infiltration, such as Rainier Mesa and Apache Leap.

6.5.1.2 Percolation to Depth: Mountain-Scale Unsaturated Zone Flow

- *Localized flow channeling.* An important uncertainty in the mountain-scale unsaturated zone flow modeling is the effect of localized channeling of flow, and in particular, the effect of flow in discrete fractures. Current modeling uses continuum models with very coarse spatial discretization, and the adequacy of this approach is not fully established. There are indications from geochemical and isotopic tracers (chloride concentration, chlorine-36 to chlorine ratio and carbon-14 to carbon ratio) that channeling of flow might be important. Better integration of geochemical, isotopic, and temperature data could improve the calibration procedure because they provide important information about flow through fractures.

- *Perched water.* The role of perched water in unsaturated zone flow is uncertain. The current model assumes that the water is perched on a very-low-permeability underlying layer and flow is forced to go around it. Other interpretations are possible, such as mixing within the perched water and matrix flow out the bottom.

6.5.1.3 Seepage into Drifts

- *Model testing.* Confidence in the seepage model could be enhanced by more comparisons between field data and model predictions. The Exploratory Studies Facility niche test is an important first step, but it is primarily a test of the overall conceptual model of the drift opening acting as a capillary barrier. The test offers little validation of the calculated values of seepage fraction, which the TSPA results show to be the most important aspect of seepage, indeed, the most important aspect of repository performance. Seepage fraction, or the fraction of waste packages contacted by seepage water, is related to the average spacing of seeps along the drift, which is presumably related to quantities such as fracture and fault spacing, permeability distribution, and permeability correlation length. Field data relating these quantities to seep spacing, possibly from analog sites such as Rainier Mesa or Apache Leap, would lend confidence to the model.

- *Localized flow channeling.* Even more so than for mountain-scale flow, seepage into drifts is potentially strongly affected by channeling of flow and discrete-fracture effects. The adequacy of the current fracture-continuum model to represent these effects is uncertain.

- *Stability of seep locations.* A potentially important issue that was not addressed in the TSPA-VA is the stability of seep locations over time. In the present models, seeps are assumed to occur at the same locations indefinitely, so that a fraction of the waste packages (the seepage fraction) is always wet and the rest are always dry. If seep locations changed with time, more waste packages would be contacted by seeps, but only for a fraction of the time. This effect could result in more waste packages failing, but over a longer period of time, which could be important for performance.

- *Drift collapse and thermal alterations of hydrologic properties.* The effect of drift collapse on seepage has not yet been investigated. Also, thermal-hydrologic-chemical or thermal-hydrologic-mechanical alteration of hydrologic properties around the drifts could have an important effect on seepage.

- *Episodic percolation.* The potential for episodic percolation pulses at the repository is uncertain. Also, drainage of thermally mobilized water could potentially cause an increase in seepage for a period of time.

6.5.1.4 Effects of Heat and Excavation on Flow: Mountain- and Drift-Scale Thermal Hydrology

- *Conceptual model of flow.* Differences have been found between results using the dual-permeability flow model and the equivalent-continuum flow model. The dual-permeability model allows for greater mobility of water in fractures, which has a great effect on modeled condensate buildup and drainage. A related flow issue, which could be important to thermal hydrology, is channelized flow, especially in discrete fractures. Such flow could greatly increase the spatial variability in the results by increasing the range of water-flow rates seen by individual waste packages.

- *Coupled processes.* A potentially important shortcoming of the thermal-hydrologic calculations is the lack of coupling to thermal-mechanical and thermal-chemical processes. These issues have been addressed to a limited extent (see Section 3.2.1), but the full range of possible (or even likely) behaviors has not been analyzed. The Near Field Environment Expert Elicitation (CRWMS M&O 1998d) will aid in considering these issues, but it was not completed until after the TSPA-VA analyses were finished. Therefore, implementing the recommendations from the expert elicitation remains to be done.

- *Thermal alterations of hydrologic properties.* Thermal alterations of flow and thermal-hydrologic-chemical or thermal-hydrologic-mechanical alterations of hydrologic properties are potentially important. In the current TSPA structure, these effects fall under the thermal-hydrology component, but thermal-hydrologic effects could be more closely coupled with mountain-scale unsaturated zone flow and transport if necessary.

- *Infiltration rate.* As shown in Section 3.2.3, infiltration rate influences computed repository temperatures. Within the range of infiltration uncertainty incorporated in the base case, the changes in temperature are not large. However, as shown in Section 5.1.3, temperature changes can still have a significant effect on computed dose rates during approximately the first 20,000 years.

- *Matrix hydrologic properties.* Almost all of the available data on matrix hydrologic properties have been obtained from drying experiments. For modeling the thermal-hydrologic behavior during rewetting and condensate drainage, data obtained from wetting experiments would be more appropriate. Wetting and drying properties can be very different because of hysteresis. The thermal-hydrologic property set mentioned in Section 3.2.3 was intended as a better representation of wetting hydrologic properties. It was found to make a significant difference to waste package failure and calculated doses for approximately the first 20,000 years, especially in the part of the repository that lies in the Topopah Spring lower nonlithophysal hydrogeologic unit (primarily Region SW of Figure 3-20).

- *Thermal response of different hydrogeologic units.* The single heater test and the heated-drift test are both located in the Topopah Spring middle nonlithophysal hydrogeologic unit. However, in the current repository design most of the emplacement drifts are in the Topopah Spring lower lithophysal unit, with some drifts in the middle nonlithophysal unit and others in the lower nonlithophysal unit. Confidence in the models would be enhanced by obtaining thermal-response data in the other two units.

- *Continued in-situ testing of thermal hydrologic models–single heater test.* The small-scale, single heater test at the Exploratory Studies Facility has provided valuable thermal-hydrologic information, including that the dual-permeability flow model and hydrologic properties used in the base case fit the measurements reasonably well, at least for the Topopah Spring middle nonlithophysal hydrogeologic unit. The single heater test results helped to guide the selection of hydrologic-property sets thermal-hydrologic models using the base case hydrologic properties match the test results better than an earlier, preliminary-base case property set (CRWMS M&O 1998i, Sec. 3.4.5).

- *Continued in-situ testing of thermal hydrologic models–drift scale test.* An important source of new information for improving thermal-hydrologic models will be the heated-drift test at the Exploratory Studies Facility. This test will provide information on drift-scale movement of heat through rock at Yucca Mountain and its impact on the flow system above and below an emplacement-sized drift. The test will include a detailed investigation of the heating period and movement of heat-driven water as well as the cooling period and subsequent rewetting analogous to the processes that would occur in the repository. Indirect measurements to detect water flow into the drift during heating will provide crucial information related to thermal refluxing processes driven by larger-scale heat-transfer processes. The data obtained from the heated-drift test will:

- Allow important verification of the conceptual flow models currently being used (or show the degree to which the current models are not adequate).
- Provide information on the effective hydrologic properties during the various stages of heating and cooling.
- Provide information on the spatial and temporal extent of mechanical and chemical changes to the fracture-flow system surrounding the heated drift. It is important to note, however, that only the results of the early heating period of the heated-drift test will be available in time for the TSPA for the LA; information on the cooling period will not yet be available.

6.5.1.5 Chemistry of Water on Waste Package: Near-Field Geochemical Environment

- *Effects of concrete-modified water.* The potential impacts from concrete-modified water compositions assessed in the sensitivity results discussed above and in Sections 5.4 and 5.6 appear to be greatest for the 10,000-year time period. The greater effects during the first 10,000 years are mainly caused by impacts to waste package performance because earlier and more frequent failures allow greater exposure of the waste form inventories at earlier times. These results suggest that further consideration be given to substituting other ground support materials for the concrete in the VA design. However, there are uncertainties within the models currently employed to evaluate the near-field geochemical environment. To better constrain changes from materials evolution in the drift, further improvements could be made in the following areas:
  - –Thermal-chemical data (both equilibrium and kinetic) for phases in the cement system, in particular at the higher temperatures expected for this system
  - –Gas composition changes in the unsaturated, thermally perturbed system
  - –Development and implementation of a two-phase, reactive transport model of concrete alteration
- *Precipitate and/or salt build up in the waste package.* Alternate conceptual models for water in the drifts and on the waste package may need to be considered. Similarly, preliminary bounds on biomass production suggest that microbial growth may be nutrient limited within the potential drifts for long periods.
- *Thermomechanical-hydrochemical coupling.* Coupled models would benefit from incorporation of more details of drift materials, both their physical-mechanical evolution and chemically-induced changes to the hydrologic properties of the engineered materials. These aspects would improve the description of water flow and radionuclide transport pathways and allow for development of more specific near-field geochemical environment scenarios.
- *Conceptual model of the near-field geochemical environment.* The updated near-field geochemical model could consider such topics as:
  - Heterogeneity of water composition flowing through the fracture system and interacting with the drift environment
  - Explicit CO_2 evolution from water and minerals coupled to the gas flow in the thermohydrologic system

- Explicit coupling of flow and geochemical reactions

- Thermal aging of all emplaced materials in dividing concrete

- Biomass production and specific microbial activity for local waste package corrosion effects

6.5.1.6 Waste Package Degradation

- *Chemical and electrochemical conditions.* The uncertainty in the current Alloy 22 corrosion model is mostly caused by the uncertainty in the local chemical and electrochemical conditions on the inner barrier and limited data on the long-term behavior of this material in the expected environment of the repository.

- *Corrosion rate of Alloy 22.* The Alloy 22 corrosion uncertainties include the general corrosion rate, localized (pitting and crevice) corrosion rate, localized corrosion initiation threshold, and understanding of the pitting and crevice corrosion stifling process.

- *Potential salt build up.* For waste packages under dripping conditions, the potential exists for salt deposit buildup on the package surface, which could produce concentrated salt solutions near the deposit. This condition could enhance corrosion of the carbon-steel outer barrier, thereby exposing the inner barrier to corrosive conditions earlier than the case without salt deposits. Long-term corrosion of carbon steel under dripping and in the presence of salt deposits is uncertain.

- *Potential galvanic coupling.* The effect of potential galvanic coupling between the Alloy 22 inner barrier and the carbon-steel outer barrier is also uncertain. The most important issue with this process is hydrogen embrittlement of Alloy 22, which could result from hydrogen pick-up by Alloy 22 over a long period and subsequent hydride precipitation inside the alloy, thus potentially shortening its lifetime. Potentially enhanced corrosion of the outer barrier from a galvanic coupling with the inner barrier is another area of uncertainty.

- *Incomplete annealing of welds.* Strengthening of the closure weld could lead to incomplete annealing of the weld. In this case, the closure weld could be subject to stress corrosion cracking.

- *Microbiologically influenced corrosion.* Microbiologically influenced corrosion was not included in the base case in part because the potential for this corrosion of the waste packages was discounted in the recent expert elicitation (CRWMS M&O 1998b). However, the process has uncertainty and could affect long term performance.

- *Long-term structural integrity.* The long-term structural integrity of the waste package is uncertain as to timing and effect. After substantial progress of degradation and under static loads from rockfall, the waste package is expected to lose its structural integrity and collapse, no longer providing a physical barrier to water ingress and radionuclide release. The threshold for waste package structural failure is currently unknown and has a potential impact on long-term repository performance.

6.5.1.7 Waste Form Alteration and Mobilization Models

- *Degradation of invert.* The invert is assumed not to degrade with time but to retain the same transport characteristics for the duration of the analyses. However, the chemistry of the invert will probably change as the system is heated during the thermal period. Heating may alter the transport characteristics of the invert. Likewise, the invert sorption characteristics are not well known and are under study. The impact of more complex invert analysis on overall system performances is not expected to be significant because of the small transport length involved relative to the total transport length.

- *Degradation of drifts.* The base case does not directly account for rock falling into the drift at later times, which is an expected condition. Although the cladding model evaluates the effects of rockfall on the cladding, the rest of the analyses do not incorporate rockfall at later times. A sensitivity to rockfall alteration of the thermal-hydrologic characteristics has been presented in Chapter 3 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i).

- *Secondary phases.* The effect of the secondary phases on subsequent radionuclide transport has been initially analyzed in Section 5.5 of the TSPA-VA. Neither the dissolution rate of the secondary phase nor the identity of radionuclides that will become fixed in the secondary phases has been well characterized. This process could have the effect of delaying radionuclide releases.

- *Seepage into the waste package.* The amount of seepage into the waste package and onto the waste form is a significant factor in releases from the engineered barrier system. How much water actually enters the waste package once it is breached is uncertain.

- *Transport resistance of failed Zircaloy cladding.* Diffusive transport out of a locally failed fuel rod is not explicitly considered and could significantly reduce release rates.

- *Chemistry-dependent solubility limits.* Additional modifications to the waste form model to improve confidence in the model include solubility-limited radionuclide distributions that are explicitly dependent on the pH and the total water composition as indicated by changing phase relations in the chemical system.

- *Chemistry-dependent sorption in the engineered barrier system.* Identifying sorption mechanisms and evaluating the dependence of sorption on the composition and mineralogy of the specific material would help to better incorporate sorption processes into the model.

- *Cladding degradation.* The current version of the cladding model provides benefit to performance but is based on assumptions about cladding degradation modes and rates. Potential cladding-failure mechanisms, such as localized corrosion and their rates, are important remaining uncertainties in the cladding analyses.

- *Water contact of waste form.* In the TSPA-VA analyses, the entire waste form surface is assumed to be exposed to aqueous conditions after the cladding fails. Detailed analyses of possible alternative models of water flow in the degraded waste package, including alternative conceptual models such as "bathtub" model would aid in evaluating the significance of the water contact mode.

- *Use of natural analogs.* The analysis of numerous uncertainties in the models, data sets, and assumptions for predicting repository performance would benefit from the use of natural analogs. Waste form degradation and mobilization and transport of radionuclides are very long-term phenomena that are difficult to evaluate with a high degree of certainty, especially if limited to information gained through short-term laboratory and field studies. Natural formations and deposits that have existed for very long periods of time show how these processes have taken place and the factors that most affect the processes. The natural "reactors" at Oklo in Gabon, Africa, have been studied extensively to evaluate the mobilization and transport of radionuclides, including plutonium, in both reducing and oxidizing environments (see, for example, Jakubick and Church 1986 p. 1; Curtis et al. 1989 p. 49; Brookins 1990 pp. 285-287; Cramer and Smellie 1994). Pena Blanca in

Chihuahua, Mexico, is a natural, high-grade uranium deposit located in unsaturated tuff that is believed to be a good analog to the Yucca Mountain repository. Further analog-oriented studies of this 8 million-year-old-deposit may provide important transport information (Murphy 1995 p. 44; Murphy et al. 1997 pp. 105-111). In addition, DOE participated in a three-year analog study at Pocos de Caldas, Brazil, which focused on radionuclide transport issues (Chapman et al. 1991 p. v).

6.5.1.8 Unsaturated Zone Transport

- *Effects of thermal-hydrologic-chemical alteration.* The current model does not account for alteration of the unsaturated zone because of thermal alteration of minerals, chemical interactions of repository materials, mineral dissolution, and precipitation. These effects are potentially important to transport behavior in the unsaturated zone. Thermal-chemical alteration could cause reduced matrix sorption and fracture/matrix interaction. The potential effects associated with alteration of the host rock and radionuclide transport pathways caused by alkaline plumes derived from the concrete masses and extending into the geosphere is not well constrained. The development of a coupled, reactive transport representation would aid the assessment of these potential effects. These effects could cause increased release rates from the unsaturated zone for base case transport results; however, the sensitivity studies (illustrated in Section 5.6) are expected to bound most of these potentially nonconservative interactions.

- *Colloid Filtration.* The ability of colloids to facilitate radionuclide transport is a function of their ability to migrate over large distances without being filtered by the host rock. This filtration effect was not included in the TSPA because of inadequate information to bound the mechanism. The filtration effect is particularly important for the fraction of radionuclides that are irreversibly bound to colloids. The assumption that there is no colloid filtration is conservative for transport in the unsaturated zone.

- *Fracture Sorption.* The effects of higher infiltration evaluated in this TSPA imply that transport will be fracture-dominated in many of the unsaturated zone units. Minerals that line fractures are known to sorb radionuclides, but more information is needed to define the distribution and character of the fracture materials so that sorption on fracture surfaces may be included. However, the assumption that radionuclides do not sorb onto fracture surfaces is conservative for transport in the unsaturated zone.

- *Matrix Diffusion.* Radionuclide transport in the unsaturated zone can be sensitive to changes in matrix diffusion depending on the nature of the release from the engineered barriers. The way in which the fracture/matrix contact area is used for calibrating the flow model suggests that some type of coupling strength may be appropriate for matrix diffusion. Sensitivity studies presented in Section 5.6 suggest that the influence of matrix diffusion on total system performance is small.

6.5.1.9 Saturated Zone Flow and Transport

- *Additional potentiometric and transport data.* Data are lacking in the saturated zone from approximately 10 km (6 miles) downgradient of the repository to the 20-km (12-mile) boundary used in the analyses. Available data in water levels, hydrochemistry and the characteristics of the alluvium are lacking in this area. Water-level measurements would improve understanding of the groundwater flow directions in this area and provide additional data for flow modeling calibration. There is uncertainty about where flow in the shallow saturated zone enters the alluvium along the flow path from the repository or even if flow occurs in the alluvium within 20 km (12 miles) of the repository. This uncertainty is particularly important given the potentially higher sorption coefficients of some radionuclides such as neptunium in the alluvium. Hydrochemical data could provide information to constrain flow paths in the model for the saturated zone in this area. Additionally, there are little site-specific data on the hydraulic, mineralogic, or geochemical characteristics of the alluvium in the saturated zone from this area.

- *Geochemical and isotopic data.* Additional geochemical and isotopic data from the saturated zone could provide important constraints on conceptual models of groundwater flow and on some key parameters for performance assessment. Enhanced vertical resolution of hydrochemical sampling could provide information on the degree of mixing in the flow system, with implications for the amount of transverse dispersion that would occur in contaminant transport from the repository. The data could also provide a better understanding of the flow paths in the saturated zone downgradient from the repository and of the magnitude of recharge to the system from Fortymile Wash. Reliable age dating of groundwater along the flow path from beneath the repository would constrain the travel times through the system and the appropriate range of values of effective porosity in the fractured volcanic tuff units. By inference, these data would provide information on the process of matrix diffusion in the fractured units. Additional electro-chemical-potential data to determine oxidation/reduction states in the saturated zone could improve sorption and solubility parameters for calculating radionuclide transport, as well as aid in the understanding of the connection between the shallow and deep aquifers at the site.

- *Three-dimensional flow and transport model.* A three-dimensional flow model for the saturated zone could provide the basis for radionuclide transport simulations that explicitly model relevant processes. An improved, site-scale flow model should be consistent with all the available data from the site. In addition, development of the flow model should be focused on simulation capabilities that are important for accurate transport modeling. These capabilities include incorporating variability and uncertainty in aquifer properties and numerical methods for simulating solute transport with minimal numerical dispersion.

- *Dispersivity and dilution.* The dilution factor for the saturated zone has been shown to be a sensitive parameter in TSPA-VA. The appropriate range for dilution and vertical transverse dispersivity is also uncertain. Reduction in the uncertainty in this parameter can benefit from inferences from analog sites or possibly from analyzing natural solute tracers in the saturated zone at the site. Additional effort could be devoted to evaluating potential analog systems of saturated flow in fractured media or in highly heterogeneous porous media.

- *Effects of climate change.* Climate change has an effect on the saturated zone that was simplified in the TSPA. For example, changes in flow paths were not considered. Changes in groundwater flux were based on regional-scale modeling but without an estimate of uncertainty. The effects of additional discharge locations and the presence of surface water were not considered. The effects of additional recharge at Yucca Mountain, Fortymile Wash, and the regions that are up gradient were also not considered. The saturated zone modeling should attempt to better reflect the wetter climates that might be normal for the Yucca Mountain region.

- *Colloid transport.* More realistic models of colloid-facilitated transport should be implemented in the saturated zone models. These models should be tied to site-scale observations of colloidal transport.

6.5.1.10 Dilution from Pumping

- *Geosphere/biosphere interface.* The geosphere/biosphere interface was defined as a well located at the point of highest concentration of contaminants in the groundwater. Natural discharge points were not considered. Dilution from mixing contaminated water with uncontaminated water during well pumping was not considered. An improved definition and modeling of this interface would lend further credibility to the calculations.

- *Pumping from Wells.* Pumping from a well could mix contaminated and uncontaminated waters—as might storing water from multiple sources in tanks—diluting any contamination. These effects have not been included in TSPA-VA (although they have been estimated in a sensitivity study presented above in Section 5.8.1). If it is determined that dilution of radionuclides by the natural environment during transport is less than the values used in TSPA-VA, it would be reasonable to examine the dilution produced during well withdrawal and storage.

6.5.1.11 Biosphere Transport and Uptake

- *Site-specific data.* The biosphere modeling indicated that the pathways that contribute the most to the calculated radiation dose rate are drinking-water ingestion, leafy-vegetable ingestion, and meat ingestion. The parameters that create the most uncertainty in these pathways are the related consumption rates, crop-interception fraction, crop-resuspension factor, grain irrigation rate, animal-uptake scale factor, and egg yield. Some of these pathways and parameters were defined based on the regional-survey data; however, additional site-specific data could improve the dose-rate calculations. The crop-interception fraction could be measured. The scaling factors for animal uptake and soil-to-plant transfer could be refined to appropriately reflect the bioavailability of radionuclides in the Amargosa Valley region and the vicinity of Yucca Mountain in general.

- *Definition of critical group and individual receptor.* For TSPA-VA, the receptor for radionuclides released from a repository at Yucca Mountain is an average member of the critical group (the reference person), to be consistent with guidance from the National Research Council (1995; p. 52). Several simplifying assumptions are made concerning the critical group: it comprises only adults; the members have habits similar to those people residing in the Amargosa Valley region today; all water for drinking and production of (locally produced) foodstuffs is the most contaminated water at 20-km (12-miles) downgradient from Yucca Mountain. It is recognized that some persons in the Amargosa Valley might be more susceptible to radionuclide contamination than the average person. Consideration of a child receptor in particular would improve the estimation of radiological effects on the critical group. It is also recognized that a better understanding of water usage and food-distribution patterns would improve the estimation of radiological effects.

- *Biosphere changes with climate.* Attempting to quantify the effect of the technological and societal advances or declines over many thousands of years is speculative. To address the influence of climate on the critical group, a comparatively small survey was conducted in Lincoln County, Nevada. This area was selected as an analog because the climatic conditions in Lincoln County are similar to those predicted for a future Amargosa Valley region. Lincoln County is approximately 200 km (120 miles) northeast of the repository site. This county is generally higher in elevation and is characterized by cooler temperatures and higher precipitation (mean annual rainfall is 2-3 times greater, depending upon elevation) than the Yucca Mountain area. However, the results from this survey were being analyzed and are not included in this report. The data gathered in the Lincoln County survey should be available to support a future TSPA.

- *Long-term build-up of radionuclides at natural discharge locations.* Modeling did not include assessments of surface soil contamination and subsequent buildup from natural discharge locations (e.g., from Franklin Lake Playa). Long-term buildup of radionuclides in natural discharge areas could alter dose calculation, especially if natural discharge affects sites of future habitation. Of interest is the amount that radionuclides might be concentrated at a natural discharge site; how these sites might be used by future inhabitants; and how much these radionuclides might subsequently be dispersed via wind or other erosional processes.

- *Well-location assumption.* All of the locally produced food consumed by the reference person was assumed to be grown with water having the same maximum levels of contamination. This assumption might be appropriate if the contaminant plume is large and well-dispersed; however, in the TSPA-VA modeling, the contamination plumes generated by a repository at Yucca Mountain would not cover the entire Amargosa Valley. This assumption might also be appropriate for a subsistence farmer; however, no one currently in the Amargosa Valley region fits this profile. Therefore, to be consistent with the current demographics and population locations, food sources could be more carefully investigated to estimate the amount of possible contamination.

- *Soil build-up.* Using contaminated water for crop irrigation can cause the buildup of radionuclide in the soils. These radionuclides can then produce an external dose and may cause additional internal doses if resuspended and contaminated soil particles are inhaled or ingested. The process of retention and buildup of radionuclides through continued irrigation with contaminated groundwater and the subsequent impacts on the various pathways defined for the biosphere could be further investigated.

6.5.2 Insights from the Total System Performance Assessment Peer Review Panel

An independent peer review of the TSPA-VA is being conducted. This peer review has the objective of providing a formal, independent evaluation and critique of the TSPA-VA in order that technical issues associated with the approach, methodology, and assumptions can be addressed prior to initiating the TSPA for the site recommendation and license application. The peer review has consisted of three interim reports to date (Whipple et al. 1997a, 1997b, and 1998) and will culminate in a final report due to be completed by the end of 1998. The Peer Review Panel consists of 6 individuals who have technical backgrounds that span the major disciplines of significance to postclosure performance, namely geohydrology, geoengineering, geochemistry, materials science, materials engineering, health physics, and risk assessment.

The Peer Review Panel has reviewed preliminary draft materials describing the approach, methodology, and assumptions to be used in the TSPA-VA as well as presentations made by the TSPA analysts to external review organizations such as NRC and the NWTRB. These materials have been supplemented by interactions of the panel members with TSPA-VA and other Yucca Mountain project staff. Although the review of the panel has been limited to date, the panel was impressed with the initial draft of Volume 3 of the Viability Assessment (Whipple et al. 1998, p. 45). However, the panel did not comment on the draft documentation of the TSPA-VA at the time of their third interim report. Ultimately the TSPA-VA Peer Review Panel will review this Volume 3 of the VA and the associated *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i) which is being prepared concurrently. This review will be completed in fiscal year 1999, with the results being used to assist DOE in prioritizing the development of the approach and methods to be used for the TSPA for the site recommendation and LA.

Based on the Peer Review Panel's reviews of the preliminary materials available to them, they have provided a range of observations, conclusions, and recommendations that must be considered in the development of the approach and methodology for the next iteration of the TSPA for the site recommendation and LA. The conclusions of the panel have been grouped into the following categories:

- Physical events and processes considered
- Use of appropriate and relevant data
- Assumptions made
- Abstraction of process models
- Application of accepted analytical methods
- Treatment of uncertainties
- Other issues

In the following paragraphs, these issues are discussed with the goal of identifying the additional models and analyses that will ultimately be required in the development of the TSPA for the site recommendation and LA. These issues may be treated as critiques of some of the assumptions made in TSPA-VA and as such some discussion is included to note the potential significance of the criticism to the conclusions reached in the TSPA-VA.

6.5.2.1 Physical Events and Processes Considered

The panel notes in their review of preliminary draft materials that the TSPA-VA has not fully addressed the potential effects associated with a number of processes. The examples they cite include coupled phenomena such as the chemical and mechanical interactions in the thermohydrologic analyses, degradation of the drift with time and the effects this may have on waste package performance, and dispersion and dilution of radionuclides in the groundwater especially at early times when small source areas may be more likely. In addition, the panel believes that too much attention may have been devoted to the potential consequences associated with low-probability disruptive events such as volcanic events.

It is acknowledged that the TSPA-VA has not addressed all processes that must eventually be evaluated as DOE proceeds from the VA to the site recommendation and licensing. Nevertheless, bounding sensitivity analyses have been performed of the potential effects associated with coupled processes by varying the fracture characteristics of the rock mass around the drift opening. These changes in fracture properties would be the principal effect of the coupled phenomena identified by the panel. The analyses presented in Section 5.1 illustrate that, within the range of parameters examined, these effects are minimal on the dose rate.

Although additional analyses are also required of the effects of drift degradation to support the site recommendation, assuming the VA reference design of no long-term support or backfill placed in the drift, some sensitivity analyses of these effects have been examined in the VA. For example, the chemical degradation of the drift liner has been examined in Section 5.3. The mechanical effects associated with drift degradation are examined in the rock fall disruptive event scenario described in Section 4.4.3. The hydrologic effects associated with drift degradation were addressed in the same sensitivity analyses related to coupled processes described above. Finally, the potential thermal effects associated with the degradation of the drift have been examined in Chapter 3 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i) and found to be inconsequential.

DOE agrees with the panel's observation that the degree of dispersion and dilution in the transport modeling should be related to the fraction of the area of the repository represented by degraded waste packages. This issue will be addressed in the analyses planned for the site recommendation and the LA. It is also important to note that the dispersion/dilution models used in the unsaturated and saturated zones as well as the assumptions made regarding the probability of the single well intersecting any dispersed plume in the alluvial aquifer must be internally consistent. In the case of TSPA-VA, it was conservatively assumed that the well intersected the highest concentration area of the plume and that there was minimal dilution in the saturated zone. This latter assumption was predicated on an expert elicitation of the saturated zone flow and transport model, in which the experts assumed that the source region was relatively large (on the order of several hundred meters) and therefore the additional dispersion effects expected in the saturated zone were minimal. If, as pointed out by the Peer Review Panel, the source region in the unsaturated zone is small, then the consistent saturated zone model should include the expected dispersive effects which are much larger (Whipple et al. 1998, p. 38). This alternative representation has been acknowledged in the assessment of the significance of unsaturated zone transport in Section 6.4. It is acknowledged that refined unsaturated and saturated zone transport models need to be investigated as part of the site recommendation and LA.

Some disruptive events are of very low probability. The probabilities of some disruptive events of interest to the long-term performance of the Yucca Mountain repository system are described in Section 4.4. Although DOE agrees that these low probability events pose very low risk to the public (as documented in Section 4.4), they are of interest to both the public and regulatory agencies such as NRC. Given this interest, DOE believes this effort has been given about the right level of attention in the TSPA-VA.

6.5.2.2 Use of Appropriate and Relevant Data

The panel notes in their review of preliminary draft materials that the TSPA-VA lacks site-specific data citing as examples the saturated zone from Forty Mile Wash to the Amargosa Valley, soil properties for determination of sorption characteristics, data on colloid transport, and radionuclide plant uptake factors. They also note that experimental data are needed to confirm the processes that control neptunium solubility and their belief that there are insufficient data to support the selection of the materials for use in the final waste package design. Finally, the panel believes that there is an over-reliance on the use of data generated by YMP scientists and only limited use of the published literature.

As DOE moves forward from the VA to the site recommendation and LA, all relevant site-specific data must be used to improve the basis for the process models. A wealth of site-specific, laboratory-derived and published literature information has been used in the course of developing the TSPA-VA. The unsaturated zone flow model has been based on extensive surface-based geologic and hydrogeologic testing, in situ observations of thermo-hydro-chemical conditions that are indicators of water movement, and laboratory studies of fundamental processes affecting water movement in fractured unsaturated media. The thermal hydrologic models have been based on in situ tests such as the single heater test and laboratory tests. These models have been compared to a wide range of similar models available in the published literature to add confidence in their relevance to the performance of the Yucca Mountain repository system. Similarly, a significant amount of laboratory testing has been conducted to evaluate the degradation characteristics and rates of the materials that are proposed to contain the wastes, in particular the candidate metals for the waste package. These tests have been complemented by information available in the published literature.

DOE will carefully consider the panel's input with regard to data availability. However, it is appropriate to acknowledge that uncertainty exists in many of the models that are used to evaluate the behavior of the Yucca Mountain repository system. This uncertainty is documented throughout this volume and in the companion *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i). Some of these uncertainties can and indeed will be reduced in the next years with an appropriate combination of site-specific field testing, laboratory testing and literature data. These additional data will be used to enhance the current understanding in those factors most significant to long term performance for use in the site recommendation and LA. The activities identified as being most important for continued testing are discussed in Volume 4, which was not available for the Peer Review Panel to review.

Despite the desire to reduce the uncertainty in many of the key components of the TSPA, it must nevertheless be acknowledged that some uncertainty will remain. As noted in the introduction to Chapter 6, this uncertainty is the result of the time and space scales of interest. The goal of the TSPA analyses is to reasonably bound this remaining uncertainty. DOE believes that the uncertainty has been reasonably bounded in the TSPA-VA. Even as efforts are made to reduce the uncertainty in the coming years, DOE will continue to assure that the remaining uncertainty, and its potential effects on postclosure performance, are appropriately addressed in the TSPA for the site recommendation and LA.

6.5.2.3 Assumptions Made

The panel notes in their review of preliminary draft materials that the TSPA-VA made some assumptions that need to be appropriately justified. They cite an example of the fully coupled thermal-hydraulic-mechanical-chemical interactions being of second order importance. In addition, they believe that incorporating other assumptions could provide useful insights into repository performance. They cite an example of prolonged ventilation of the repository.

DOE agrees that all assumptions need to be appropriately justified and their significance to long term performance evaluated. The purpose of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i) is to provide the appropriate rationale with the supporting data, analyses and references to relevant project information, including the process model for each TSPA component. In the particular example cited by the panel, the significance of the complex process interactions mentioned has been evaluated with a range of individual sensitivity studies. For example, the seepage model has been modified to account for either an increase or decrease in fracture permeability and capillarity that might be the result of these coupled processes. These results indicate that the overall performance is not significantly sensitive to such changes, which is the basis of the assumption. DOE acknowledges that it will be very difficult to predict with any degree of robustness the exact thermal-hydraulic-mechanical-chemical interactions that might occur in each drift in the vicinity of each waste package. However, such fidelity in the analysis is not required. What is required is to reasonably bound the potential effects so that informed decisions can be made about the potential safety of the repository system.

DOE agrees that a range of alternative assumptions needs to be evaluated to gain sufficient understanding of how the system is likely to perform. Many of these alternative assumptions have been explored in Chapters 4 and 5 of this volume. Most of these have relied on the VA reference design, which does not include long term ventilation. Many others, including a range of alternative designs such as the long-term ventilation design mentioned by the panel, are worthy of investigation. These alternative designs and design features will be a major emphasis of the Project in fiscal year 1999 as DOE moves forward to selecting the appropriate site recommendation and LA design.

6.5.2.4 Abstraction of Process Models

The panel notes in their review of preliminary draft materials that the abstraction process used in the TSPA-VA needs to be reviewed. In particular they note that an abstracted model should only be used if the process-level model upon which the abstraction is based confirms its use is justified. They also note that there needs to be appropriate integration of the abstracted models among the different groups developing the TSPA. They cite an example related to the consistency between unsaturated zone and saturated zone transport model assumptions.

The abstracted models used in TSPA-VA have been based either on an underlying process model or the basic data that describe the relevant process. All models, whether process-based or abstracted, are abstractions of reality. All models, whether process-based or abstractions, need to be compared to appropriate in-situ or laboratory observations. Unfortunately, there are minimal opportunities to compare the results of the models over the spatial and temporal scales of interest to direct observations, with the exception of some natural analogs.

The *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i) describes the details of the abstraction for each of the components of the TSPA-VA. In the case of the abstracted models of unsaturated zone flow, seepage into drifts, thermal hydrology, waste package degradation, cladding degradation, unsaturated zone transport, and biosphere transport the abstracted models are based directly on the underlying process model. In some cases the model was directly used in the TSPA analyses while in other cases a response surface capturing the relevant results of the process model was used. In the case of abstracted models of climate change, waste form degradation, radionuclide solubility, colloid stability and mobility, and saturated zone transport the abstracted models are based directly on available externally published or project-generated global, regional, site and laboratory data. Therefore, DOE believes there is a good, even if preliminary, technical basis for all the models used in the TSPA-VA.

Nevertheless, DOE understands the Peer Review caution that all models and assumptions need to be appropriately justified when used in the development of a license application. Therefore, a range of activities that are summarized in Volume 4 will be undertaken over the next few years with their aim being to enhance the confidence in all models used to make projections of repository performance.

DOE agrees that the assumptions made between different abstracted models need to be self consistent. Every effort was made in the TSPA-VA to assure this. For example, if different assumptions were made about infiltration rates, these were consistently applied through the system to evaluate changes in percolation flux, seepage fraction and flux, thermal hydrologic response, unsaturated zone groundwater velocity, and the water table elevation. An additional example is the propagation of transient changes through the system. If the climate was assumed to change at a particular time, then this change was propagated through changes in the unsaturated zone flow and transport, seepage, water table elevation and saturated zone flow and transport. DOE will continue to strive to assure that assumptions made between different components of the TSPA remain consistent.

An additional consistency issue noted by the panel centers around the depiction of contaminant plume dispersion in both the unsaturated and saturated zones. DOE agrees these need to be consistent. As noted above in the discussion in Section 6.5.2.1, the TSPA-VA assumed that the pumping well directly intersected the maximum concentration of the plume, that there was no mixing in the pumping well and that there was minimal dispersion in the saturated zone. This was the result of basing the dispersion effects on an expert elicitation which assumed the plume size entering the saturated zone was on the order of several hundred meters in width, that is the plume had already been dispersed in the unsaturated zone. As the panel points out, this assumption, may be appropriate at late times (several hundred thousand years) when waste packages located over a significant fraction of the area of the repository may be expected to be contributing to releases. However, this assumption is probably inappropriate at early times (less than 10,000 years) when only a very few breached waste packages are contributing to the dose rate. To be consistent, if a model of transport from discrete waste packages is invoked in the unsaturated zone, then the likely dispersion in the saturated zone and well intersection probability should be included in the analyses. These will be investigated in the TSPA for the site recommendation and LA.

6.5.2.5 Application of Accepted Analytical Methods

The panel notes in their review of preliminary draft materials that the TSPA-VA may contain models that contain uncertainties. In some cases they note that these models may have been applied without recognition of their potential limitations. They comment that these limitations could call into question the usefulness of the sensitivity and uncertainty analyses that have been conducted. They cite several models that exemplify their concern:

1. The saturated zone flow model

2. The thermal hydrology model including the coupled effects of thermochemical and thermo-mechanical interactions

3. The unsaturated zone flow model including the seepage model

4. The unsaturated zone transport model including the mechanisms of colloid migration

5. The waste package degradation model including the effects of crevice corrosion, chemical conditions on the waste package surface, stress corrosion cracking, and the generation of corrosion products in crevices between the outer and inner waste package materials

6. The cladding degradation model including its uncertainty

7. The saturated zone flow and transport model including greater resolution of the numerical representation

In addition to these individual models, they note that the relevant hypotheses, models and abstractions need to be verified by comparison to appropriate site-specific, laboratory or literature data.

DOE agrees that uncertainties exist in all the cited models. These uncertainties have been the focus of a number of workshops that DOE has held on the key components of the TSPA (see Table 2-2 for a complete listing of these workshops and expert elicitations). These uncertainties have also been documented in the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i).

One of the goals of the TSPA-VA is to examine the significance of these uncertainties on postclosure performance to assist in identifying the key factors requiring additional information prior to the submittal of the site recommendation and LA. As noted in Section 4.3 and Chapter 5, the significance of these uncertainties was investigated using both a range of parameters and models to describe the base case performance, as well as a suite of alternative models that were tested to determine whether differing assumptions would significantly change the results.

In all of the examples cited by the Peer Review Panel, at least one and in many cases several sensitivity analyses have been conducted to investigate the potential significance of the noted uncertainty. For example, a range of different seepage models has been studied to accommodate the most significant aspect of coupled processes (Section 5.1). A range of different assumptions regarding the waste package degradation model (including the fraction of the waste package with seepage, the size of the patches, and the distribution of the local chemistry on the waste package surface) has also been investigated (Section 5.4). Analyses have been performed using a range of distributions for the Zircaloy cladding degradation (Section 5.5). These included one case in which it was assumed there was no performance credit for the cladding.

DOE believes that the above sensitivity analyses and others described in Chapter 4 and 5 capture the range of likely performance of the repository system. Although it is possible to combine low probability models and parameters to further investigate the full range of performance, the results of these scenarios would have to be appropriately weighted by their low probability. Such analyses may be required in the licensing of the Yucca Mountain repository, but they were not the focus of the Viability Assessment, which was designed to investigate the probable behavior of the repository system.

DOE agrees that uncertainties other than those quantified in the TSPA-VA do exist. The panel correctly points out some of these. These uncertainties, as well as their potential significance need to be investigated prior to the site recommendation and LA.

In several instances, the Peer Review Panel notes the need to reduce the uncertainty that has been identified (whether that identification was by DOE, by the Peer Review Panel, by the NWTRB or by NRC). Although in many areas, there will be significant work performed over the next several years to minimize the uncertainty in models and abstractions for use in the TSPA for the site recommendation and LA, DOE acknowledges that even after this effort, uncertainties will still remain. The goal of the next TSPA analyses will be to address the significance of the remaining uncertainties and assure that the site and associated engineered barriers meets with a sufficient safety margin all applicable environmental and safety standards.

6.5.2.6 Treatment of Uncertainties

The panel notes in their review of preliminary draft materials that the TSPA-VA has "lumped" many types of uncertainties and that the results may be inappropriately insensitive to some aspects of the actual behavior of the repository system. In addition, the panel observes that the TSPA-VA has not provided adequate consideration of the multitude of factors that are necessary for estimating dose rates to the public.

DOE agrees that many types of uncertainty have been evaluated as part of the TSPA-VA. Assuming that all the relevant uncertainties were adequately characterized, quantified and incorporated in the models used for projecting system behavior, the system model should be able to determine the relative sensitivity of the system behavior to each of the model components. However, it must be acknowledged that not all uncertainties of all types have been included in the single system model used in TSPA-VA. To better investigate the complex interrelationships between the different system components, a number of alternative model sensitivity analyses were developed and documented in Chapter 5. These analyses were conducted in part to examine whether the initial results were indeed "inappropriately insensitive". DOE believes that the combined suite of sensitivity analyses have captured the range in probable behavior of the Yucca Mountain repository system.

DOE is aware of the many factors that contribute to the estimate of dose from a given radionuclide concentration in the groundwater. All of these factors are included in the model used to estimate biosphere dose conversion factors. Reasonable ranges for the key factors have been used in the development of the distribution of biosphere dose conversion factors. These distributions will be examined, including the sources and magnitudes of their uncertainty, prior to the development of the TSPA for the site recommendation and LA.

6.5.2.7 Other Issues

Based on the preliminary information available to the panel, they questioned the apparent focus of the TSPA-VA almost exclusively on the time period from 10,000 to 1 million years. They also note the need for additional supporting research in a number of areas, including water compositions in contact with the waste package, critical crevice corrosion temperatures, neptunium solubility and technetium sorption on degraded waste package materials.

DOE does not believe it focussed on any particular time frame in the analyses presented in Chapters 4 and 5. Generally, the results are displayed and discussed in three different time periods, the time from closure to 10,000 years, the time from 10,000 to 100,000 years and finally the time period from 100,000 to 1 million years. This has been done for several different reasons. First, the significance of the overall system response is difficult to examine in a single time period. Second, different insights are gained by examining the results over different time periods. Third, DOE does not know over what time period the environmental and regulatory performance objectives will be applied although preliminary indications are that the 10,000 year period will likely be addressed with quantitative performance requirements in the new regulations being prepared for Yucca Mountain. Finally, it is believed that conducting analyses to the time of the peak dose, whenever that occurs, allows some confidence in a more comprehensive, even if more qualitative, evaluation of the performance of the entire system.

As noted by the panel, the time period of interest is an important aspect of the defense in depth strategy that will evolve during development of the license application, and will undoubtedly be the subject of extensive discussion between NRC and DOE during licensing proceedings. The performance allocation approach presented in Volume 4 is consistent with the general approach taken to date, which assumes that both 10,000 year performance and peak dose are important performance measures.

DOE acknowledges the need for additional investigations in a number of areas, including those mentioned in the panel's report. The investigations that are planned over the next few years are those that would significantly improve upon the current understanding and which are significant to the system performance. The planned activities are described in Volume 4.

In summary, interactions with the Peer Review Panel continue to provide useful feedback as DOE moves forward to develop the basis for the next iteration of TSPA. Their Third Interim Report points to a number of areas where attention will need to be placed as the basis for the site recommendation and license application is prepared.

6.5.3 Comments from the Nuclear Regulatory Commission

NRC has recently provided DOE with initial comments on the TSPA-VA (Letter from Michael J. Bell, NRC to Stephan J. Brocoum, DOE, dated July 6, 1998). These comments were based on a series of three Technical Exchanges held between DOE and NRC staffs and their contractors, the most recent being in March, 1998. As noted in the letter, NRC comments are intended to facilitate DOE's effort to identify the future work that may be needed to develop a complete and acceptable license application.

DOE appreciates the opportunity to interact with NRC staff on the significant issues associated with assessing the long-term performance of the Yucca Mountain repository system. The comments provided by NRC during the Technical Exchanges and the above letter, in conjunction with the recently published Issue Resolution Status Report for Total System Performance Assessment and Integration (NRC 1998a) assist DOE in identifying the most relevant issues to NRC which can then be a basis for continued discussion and ultimately closure.

In the following paragraphs, each of the NRC comments is presented and briefly discussed. Where appropriate, the reader is referred to Volume 4, which contains descriptions of the activities DOE intends to conduct between now and the completion of the Site Recommendation Report and the submittal of the LA.

6.5.3.1 Radionuclides Tracked in the Performance Assessment

DOE concurs that the approach used for screening out unimportant radionuclides from the TSPA analyses needs to be well documented and the potential impacts of not considering the full suite of possible radionuclides present needs to be demonstrated. The radionuclide screening process is summarized in Section 3.5 of the TSPA-VA. The details of the implementation of this process and the small differences arising from not considering a full suite of radionuclides are discussed in Chapter 6 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i). Given that the suite of potentially important radionuclides may vary with the specific design, modeling assumptions, and scenarios analyzed, it is agreed that each TSPA analysis should address this issue and justify the inclusion or exclusion of certain radionuclides. DOE will continue to carefully review the assumptions of the radionuclides included in the TSPA analyses for the site recommendation and LA.

6.5.3.2 Consideration of all Significant Features and Processes in the Performance Assessment

DOE agrees that the rationale for including or excluding any potentially significant feature, event or process needs to be technically justified and clearly articulated. The rationale used in the TSPA-VA has been presented in the detailed descriptions of each component model documented in the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O1998i). Acknowledging that there is uncertainty in exactly what features, events and processes are most significant to long-term performance, a range of total system sensitivity analyses have been conducted in the TSPA-VA (Chapter 5). These analyses, together with subsystem and component model sensitivity analyses that are presented in the *Total System Performance Assessment-Viability*

Assessment (TSPA-VA) Analyses Technical Basis Document (CRWMS M&O 1998i) form the basis for the determination of importance. As DOE proceeds from the VA to the site recommendation and LA, these analyses will be expanded to include other potentially important features, events and processes, along with appropriate auxiliary analyses to support the resolution of relevant sub-issues in some of the NRC KTIs. All of these analyses will be documented in the LA.

6.5.3.3 Model Abstraction

DOE agrees that modeling assumptions should be consistent across different process models, unless there is a defensible technical rationale. An example of a case where different assumptions may be appropriate is the spatial and temporal averaging of hydraulic properties. Flow properties applicable at the scale of tens of meters (e.g., analyses in the vicinity of the drift) would be different than hydraulic properties hundred of meters (e.g., analysis of flow from the repository to the water table). Although the two parameter sets should be consistent, they may be different.

Every effort is being made through the document review process to ensure consistency of key parameters across both process models and abstracted models used in the TSPA-VA. For example, the climate change is propagated through the system by affecting the infiltration rate, percolation rate, seepage rate, groundwater velocity, water table rise and saturated zone flux. DOE will continue to rely on its internal and external review processes to ensure that the individual models and their coupling are appropriately consistent. In addition, DOE will use pre-licensing interactions and technical exchanges with NRC to check its effectiveness, as it proceeds with preparing the TSPA for the LA.

6.5.3.4 Documentation of Assumptions

DOE agrees that detailed documentation of the assumptions used in performance assessments is of fundamental importance to the transparency (and credibility) of the TSPA. This was the objective of producing a companion document, the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i), which augments the TSPA-VA documentation contained in Volume 3 of the VA. This documentation has undergone several internal reviews, with part of the review criteria being based on the NRC criteria noted in their Issue Resolution Status Report on Total System Performance Assessment (NRC 1998a). The documentation of the TSPA-VA model assumptions will ultimately be reviewed by the TSPA-VA Peer Review Panel, NRC and their contractors, the NWTRB, the State of Nevada, and by other interested parties. All comments received will help DOE ensure that the documentation for the TSPA for the site recommendation and LA is sufficient to facilitate regulatory review.

6.5.3.5 Transparency and Traceability of Analysis

DOE concurs with NRC comment that the performance assessment results should allow the importance of alternative models to be evaluated. This was the goal of the sensitivity analyses presented in Section 5. Based on previous NRC comments on this subject, as those from the NWTRB on this same subject, DOE is making a concerted effort to improve the graphical presentation and documentation of these diverse and multifaceted analyses. DOE expects to discuss this issue at future Technical Exchanges with NRC on their TSPA Methodology Issue Resolution Status Report, and through DOE's internal review process for technical reports.

6.5.3.6 Container Life

DOE agrees that the technical basis for the degradation characteristics and rates of the candidate waste package materials needs to be adequately justified. The basis for the model used in the TSPA-VA is described briefly in Section 3.4 of Volume 3 of the VA and in Chapter 5 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i) along with the supporting documentation that is cited in these documents. DOE agrees that the basis must be enhanced further in the next few years leading to the LA design and performance assessment. The work to provide this additional confidence is described in Volume 4.

6.5.3.7 Role of Rockfall in Assessing Waste Package Lifetime

DOE agrees that rockfall effects need to be considered in the design and performance of the Yucca Mountain repository system. In the TSPA-VA this has been addressed with some explicit analyses of seismically-induced rockfall damage in Section 4.4.3 and an implicit incorporation of early waste package failures caused by unanticipated processes. These early juvenile failures were incorporated in the base case analyses after the NRC-DOE Technical Exchange in March, 1998. Continued definition of the potential consequences of early waste package failures will occur as part of the multiple barrier analyses expected to be performed for the TSPA for the site recommendation and LA. In addition, DOE plans to pursue dialog on this topic through its interactions with NRC in future Technical Exchanges.

6.5.3.8 Effectiveness of Engineered Barriers in the Event of Volcanic Activity

In the TSPA-VA, DOE has analyzed the potential consequences associated with low probability volcanic activity at Yucca Mountain. In these analyses, reasonably conservative assumptions were made regarding the potential waste package failure modes (presuming that such an event occurred.) Although alternative failure modes could be postulated, DOE believes that the analyses presented in the VA are sufficient to bound the potential risk (equal to the probability of the event times the consequences of the event) of the direct volcanic intrusion scenario. Alternative failure modes may be addressed in the TSPA for the site recommendation and LA and DOE plans to pursue dialog on this and other disruptive events and processes with NRC staff and their contractors as part of the ongoing DOE/NRC Technical Exchanges on TSPA and future interactions on the NRC TSPA Methodology Issue Resolution Status Report (i.e., as part of resolution activities on the scenario analysis subissue).

6.5.3.9 Neptunium Solubilities

DOE concurs that the basis for the selection of the neptunium solubility used in the TSPA analyses needs to be supported by applicable measurements under suitable conditions. The rationale for the statistical distribution used in TSPA-VA has been based on available laboratory measurements combined with information on the stability of various neptunium phases in different geochemical environments. This rationale is presented in Section 3.5. Because of the importance of neptunium to long-term dose assessments (see Section 5.5), DOE will continue to refine the estimates of the range of neptunium solubility values for use in the TSPA for the site recommendation and LA.

6.5.3.10 Matrix Diffusion

DOE agrees that the technical basis for differing assumptions about matrix diffusion need to be documented. These have been included in Section 3.6 and in Chapter 7 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i). In addition, a range of sensitivity analyses have been conducted with differing assumptions about matrix diffusion. These results are presented in Sections 5.6 and 5.7. DOE will continue to review this issue with NRC in future Technical Exchanges and Appendix 7 meetings to ensure that a defensible and reasonably conservative representation of this transport process is included in subsequent TSPAs for the repository.

6.5.3.11 Saturated Zone Transport

NRC notes that there are limited data to define the saturated zone transport along the groundwater pathway south of the repository to the postulated receptor location at 20 km (12 miles). DOE also recognizes the current dearth of hydrogeologic data in this region of the flow system. DOE also agrees that both the incorporation of additional field data, such as the data to be collected from the Nye County well network, and models which incorporate the uncertainty in the flow and transport characteristics are essential to the preparation of a complete and defensible TSPA for the proposed repository system.

6.5.3.12 Radionuclide Retardation

DOE agrees that the technical basis for sorption coefficients used in the TSPA analyses needs to be improved and more substantive. For the TSPA-VA, this basis is presented in Chapter 7 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i). The basis for application of any laboratory-derived sorption coefficients, and the analogs that are used to define correlations, needs to reasonably represent the uncertainty in this parameter. DOE will continue its effort to enhance the documentation of the basis for all assumptions as it moves forward from the VA to the site recommendation and LA.

6.5.3.13 Treatment of Colloids

DOE agrees that the mechanistic basis for the partitioning coefficient for plutonium sorption onto colloids, as well as the stability and filtration characteristics of these colloids, needs to be better defined between the VA and the site recommendation and LA. Efforts to better characterize the colloid distribution and reversibility are planned. These efforts are summarized in Volume 4.

6.5.3.14 Basis for Assigning Probabilities to Corrosion Potential Values

NRC notes that specific probabilities of different corrosion potentials, that have been derived from expert elicitation, have been used in the waste package degradation model of the TSPA-VA. The basis for these distributions is presented in Chapter 5 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i) as well as the expert elicitation report on waste package degradation (CRWMS M&O 1998b). As described in Volume 4, continued testing is underway to verify the corrosion potential distributions that should be used in future TSPAs.

6.5.3.15 Uncertainty in the Results of Expert Elicitation

NRC comments that the significance of the uncertainty representations in the expert elicitation results should be propagated through the total-system calculation. They cite an example of the point-value probabilities used to define the corrosion potential of Alloy 22. DOE concurs with this assessment. In fact, the sensitivity to this parameter was evaluated and documented in Chapter 5 of the *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998i). As DOE continues toward the development of the site recommendation and LA, the uncertainty in all significant factors affecting postclosure performance will be investigated.

6.5.3.16 Development of Expert Elicitation Results for Use in Performance Assessment

NRC comments that in some cases, the cited example being the Probabilistic Seismic Hazard Analysis, the panel of experts did not have a clear understanding of how their results would be used in the performance assessment. In all of the elicitations conducted specifically for TSPA-VA, however, the CRWMS M&O presented the goals and objectives of the elicitation as well as exactly how the results were to be used. The goal of the cited seismic hazard analysis was focussed on inputs to the preclosure design and safety aspects of the surface and subsurface facilities as opposed to the postclosure performance assessments. DOE agrees that experts used in formal elicitations should be informed at the outset how the results of the elicited judgments will be used.

In summary, DOE finds the comments that NRC (and their contractors at the Center for Nuclear Waste Regulatory Analyses at the Southwest Research Institute) have made during and after the Technical Exchanges held over the last year to be very constructive and helpful. DOE anticipates that NRC will comment on the Viability Assessment when it is formally released. DOE believes that these comments in conjunction with meetings on each of the individual Issue

Resolution Status Reports will assist DOE in working towards a defensible LA.

6.5.4 Concluding Remarks

Current data and analyses indicate that the Yucca Mountain site provides favorable features for limiting the contact of water with the waste. The location of the site in a semiarid region and the nature of the site itself limit the amount of water that can reach the repository. The site provides a thick unsaturated zone where the waste can be placed deep below the surface and well above the water table; the waste packages would therefore be protected from changes in conditions at the surface while still being kept well away from the saturated zone. The site would therefore provide predictable and stable environments for design of engineered barriers that could further limit the exposure of waste to water.

Performance assessment and design studies indicate that there are a number of options for the design to keep water away from the waste. They indicate, for example, that the highly corrosion-resistant inner container and the thick steel outer container of the reference design of this VA each provide effective barriers against water. Although as noted above there are some issues that must still be addressed, the estimates indicate that robust waste packages could be designed to remain intact for thousands of years in the repository environments. The studies also indicate that the spent nuclear fuel cladding would likely provide an additional barrier to water contacting the waste, once the outer and inner waste package barriers are breached.

In addition to expected repository performance, the postclosure safety case also explicitly considers processes and events that could disrupt a repository at the Yucca Mountain site. These include disruptive natural processes (seismicity and volcanism), potential human intrusion associated with exploration for natural resources, and nuclear criticality. Each of these potentially disruptive processes and events has been examined in this volume. The analyses presented in Section 4.4 indicate these disruptive scenarios introduce no substantial increase in the risk to long-term public health or safety.

As noted in the Introduction (Volume 1), a number of investigations are required to assist DOE in developing the safety case for the Yucca Mountain repository system. The safety case is comprised not only of evaluations of total system performance similar to those documented in this volume, but also of evaluations of multiple barriers, treatment of the safety margin, and use of natural analogs as qualitative indicators of expected behavior. In addition, the total safety case must consider the operational and preclosure safety of the workers and the public, rather than solely the long-term postclosure aspects evaluated in TSPA.

The goal of each successive total system performance assessment iteration is to refine the analyses based on improved site understanding and the maturation of the design concepts for the engineered system. Using the results of the performance assessments documented in this volume and summarized in the previous portions of this section, the key attributes and principal factors likely to affect the LA performance assessment have been identified and prioritized.

The effects of uncertainty included in the analyses of the principal factors affecting postclosure performance projections for the reference design were identified and ranked in Section 6.4. These rankings provide a partial basis for prioritizing investigations to reduce the uncertainty in these factors. However, there is also additional information in the form of judgment that must also be incorporated in the rankings. Finally, although uncertainty in a specific factor may have a large effect on the final result of a TSPA analysis, reduction of that uncertainty may not be possible. This may be true because of prohibitive cost of a study, lack of technology to address a specific question, or lack of adequate time to complete a study before the LA submission deadline.

Therefore, prioritization of the principle factors, and the work needed to characterize each of them in the TSPA, is conditional based on the reference design and the TSPA modeling and assumptions. Reduction in uncertainty may not be practical, or even possible, for some of the factors that are most important to performance. Some of the factors that are most important to performance may already be sufficiently well characterized. The importance of some factors may be obviated by a change in the repository design. Only where data are deemed inadequate and can be improved from a practical perspective, and should be improved from a licensing perspective, will additional work be performed.

The TSPA-VA indicates that for the first 10,000 years the expected dose rate derived from the repository at Yucca Mountain is essentially zero. Even within the first 100,000 years, the anticipated dose rate from a repository at Yucca Mountain is less than the national average for radiation from non-medical sources (approximately 300 mrem/year). Only at time scales of greater than 100,000 years does the additional dose rate from a repository approach the average background dose rate. The TSPA-VA also finds that the engineered system in the reference design has considerable impact on repository performance for a long period, on the order of several hundred thousand years. For even longer periods of time, however, the natural system dominates performance. The TSPA-VA shows that some factors and how they are modeled can have especially important influences on performance: for example, the corrosion characteristics of Alloy 22, the dilution of radionuclides in the transport pathways, and the transport of radionuclides as colloids. The TSPA-VA reinforces some ideas about performance; for example, that it is important to isolate waste from advective flow and that, for a dose-based standard, the rate of releases of radionuclides from a repository and the dilution in the environment are important. And finally, the TSPA-VA points out areas where improvements could be made to the TSPA models and data, including the most important uncertainties that could be reduced and the most important assumptions that could be addressed in the future.

The prioritization of the information needed to address the principal factors affecting expected postclosure performance allows focusing the testing and analysis programs on the key remaining questions related to repository performance. This prioritization and the rationale behind the allocation for each principle factor is given in Volume 4. The schedule for addressing these issues is also found in Volume 4.

The analyses of the TSPA-VA will provide a large part of the basis for the work required for construction of the TSPA for the site recommendation and the LA. However, as discussed above, the specific analysis results do not tell the entire story. In some cases, there was little applicable data available at the time for developing a model of a given factor. In other areas, because site characterization and design activities are still ongoing, new information has indicated that the ranges of values used may have been incomplete or too large. In each such case, it was necessary for the analysts to use judgment, based on their experience, to interpret the validity of their results. Where judgment has been used to modify the relative influence of uncertainty of a factor to be different than that shown by analysis (as documented in Volume 4), there is clearly a need to improve the confidence in the model for that factor. In addition, independent groups, such as the TSPA Peer Review Panel and the Nuclear Regulatory Commission, have provided suggestions of areas where more work is necessary to develop adequate TSPA models.

The next step for the Yucca Mountain TSPA team is to develop a comprehensive plan for addressing the important issues. While the general outline of this plan is contained in Volume 4, many details of the specific modeling activities must still be developed. A series of abstraction and testing activities, involving investigators from site characterization, design, and the performance assessment organizations will be convened to determine how to best incorporate the available information into appropriate representations of the total system. Because it will not be possible to develop these models to the same degree of complexity, the relative sensitivity of the factor will determine how much effort will be expended to improve any specific model or parameter. The outcome of these activities is anticipated to result in an improved set of total-system performance assessment models. These models will provide DOE with the reasonable assurance required to understand how the system will behave and the degree of safety the system will provide to the public.

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7.2 STANDARDS AND REGULATIONS

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10 CFR (*Code of Federal Regulations*) 60. Energy: Disposal of High-Level Radioactive Wastes in Geologic Repositories; Technical Criteria; Final Rule. 238445.

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APPENDIX A

GLOSSARY

APPENDIX A

GLOSSARY

The glossary is divided into two sections. Section A.1 is a general glossary of terms used in the TSPA-VA; Section A.2 contains a listing of statistical terms that are used in or are relevant to other statistical terms used in the TSPA-VA. Definitions are written with emphasis on the relationship of the term to the TSPA-VA process and are taken from previous performance-assessment documentation, where possible, or from standard reference materials.

Many of the definitions in this Glossary are Yucca Mountain Site Characterization Project specific.

A.1 GENERAL GLOSSARY

This section is a general listing of terms used in the TSPA-VA. Statistical terms are in Section A.2.

Abiotic	Characterized by the absence of living organisms.
Absorbed Dose	The energy absorbed from ionizing radiation per unit mass of irradiated material. Units of absorbed dose are the rad and the gray (Gy).
Abstracted Model	Model that reproduces, or bounds, the essential elements of a more detailed process model and captures uncertainty and variability in what is often, but not always, a simplified or idealized form. See Abstraction.
Abstraction	Distillation of the essential components of a process model into a suitable form for use in a total system performance assessment. The distillation must retain the basic intrinsic form of the process model but does not usually require its original complexity. Model abstraction is usually necessary to maximize the use of limited computational resources while allowing a sufficient range of sensitivity and uncertainty analyses.
Actinides	A series of chemically similar, mostly synthetic, radioactive elements with atomic numbers from 89 (actinium) through 103 (lawrencium).
Activity	Cumulative curie count. See Radioactivity.
Adsorb	To collect a gas, liquid, or dissolved substance on a surface as a condensed layer.
Adsorbate	A substance that is adsorbed. See Adsorb.
Adsorbent	A substance upon which another substance is adsorbed. See Adsorb.
Adsorption	Transfer of solute mass, such as radionuclides, in groundwater to the solid geologic surfaces with which it comes in contact. The term sorption is sometimes used interchangeably with this term.

Adsorption Isotherm	Relationship of the quantity of an adsorbed component to its quantity in the fluid phase (expressed in concentration) at constant temperature (i.e., under isothermal conditions).
Adsorption Coefficient	See Sorption Coefficient.
Advection	The process in which solutes are transported by the motion of flowing groundwater. Advection in combination with dispersion (hydrodynamic dispersion) controls flux into and out of the elemental volumes of the flow domain in groundwater transport models. The term convection is sometimes used for advection but is not used interchangeably in the TSPA-VA.
Advisory Committee On Nuclear Waste	A committee established under the Nuclear Regulatory Commission to provide independent reviews of, and advice on, nuclear waste facilities, including application to such facilities of 10 CFR Parts 60 and 61 (disposal of high-level radioactive wastes in geologic repositories and land disposal of radioactive waste) and other applicable regulations and legislative mandates.
Aerobic	Living or active only in the presence of oxygen, as used in reference to bacteria that require oxygen; a condition in which oxygen is present.
Air Mass Fraction	Mass of air divided by the total mass of gas (typically air plus water vapor) in the gas phase. This expression gives a measure of the "dryness" of the gas phase, which is important in waste package corrosion models.
Algorithm	(1) The set of well-defined rules that governs the solution of a problem in a finite number of steps. (2) A mathematical formulation of a model of a physical process.
Alkaline	See pH.
Alloy 22	See Inner Barrier.
Alluvium	Sedimentary material (clay, mud, sand, silt, gravel) deposited by flowing water or by wind.
Alternative	Plausible interpretations or designs based on assumptions other than those used in the base case that could also fit or be applicable based on the available scientific information. When propagated through a quantitative tool such as performance assessment, alternative interpretations can illustrate the significance of the uncertainty in the base case interpretation chosen to represent the repository's probable behavior.
Ambient	(1) Undisturbed, natural conditions such as ambient temperature caused by climate or natural subsurface thermal gradients. (2) Surrounding conditions.

Anaerobic	(1) Living or active only in the absence of oxygen; used in reference to bacteria that do not require oxygen. (2) A condition in which oxygen is absent.
Anionic	An atom or group of atoms having a negative charge.
Anisotropy	The condition in which physical properties vary when measured in different directions or along different axes. For example, in a layered rock section the permeability is often anisotropic in the vertical direction from layer to layer but is isotropic in the horizontal direction within a layer.
Annual Dose	For human exposure scenarios, a measure of an individual's exposure to radiation in a year.
Annual Committed Effective Dose Equivalent	Composed of terms in 40 CFR 191, Subpart B, in which an annual committed effective dose means the committed effective dose caused by 1-year intake from released radionuclides plus the annual effective dose caused by direct radiation from facilities or activities. See Effective Dose Equivalent and Committed Dose Equivalent.
Annual Frequency	Number of occurrences on an annual basis.
Anthropogenic	Alterations of the environment resulting from the presence or activities of humans.
Aqueous	Pertaining to water, such as aqueous phase, aqueous species, or aqueous transport.
Aquifer	A subsurface, saturated rock unit (formation, group of formations, or part of a formation) of sufficient permeability to transmit groundwater and yield usable quantities of water to wells and springs.
Areal Mass Loading	Used in thermal loading calculations, the amount of heavy metal (usually expressed in metric tons of uranium or equivalent) emplaced per unit area in the proposed repository. This number is 85 metric tons of uranium (MTU) per acre and remains a constant value over time for calculations in which the amount of waste per acre in the repository is assumed to remain constant.
AREST-CT Computer Program	A general modeling code that considers both equilibrium and kinetically controlled chemical reactions between solid phases, aqueous solutions, and gas under flowing conditions.
Average Individual	An individual representative of the life style in the Amargosa Valley with regard to eating, drinking, and other activities that may be relevant in a human exposure scenario as determined by a survey of Amargosa Valley residents by TSPA-VA researchers.

Backfill	The general fill that is placed in the excavated areas of the underground facility. If used, the backfill for the repository may be tuff or other material.
Background Radiation	Radiation arising from natural radioactive material always present in the environment, including solar and cosmic radiation, radon gas, soil and rocks, and the human body.
Basalt	A dark, fine-grained igneous rock originating from a lava flow or minor intrusion, composed mainly of plagioclase clinopyroxene and sometimes olivine, and often displaying a columnar structure.
Base Case	The sequence of anticipated conditions expected to occur in and around the proposed repository, without the inclusion of unlikely or unanticipated features, events, or processes. The components that contribute to the base case model are intended to encompass this probable behavior of the repository, based on the range of uncertainty for the various parameters and conceptual models used in constructing the base case.
Base Case Model	A computer model that represents an assessment of the most likely range of behavior for the overall repository system and is a combination of the most likely ranges of behavior for the various component models, processes, and associated parameters.
Biosphere	The ecosystem of the earth and the living organisms inhabiting it.
Biosphere Dose Conversion Factor	A multiplier used in converting a radionuclide concentration at the geosphere/biosphere interface into a dose that a human would experience for all pathways considered, with units expressed in terms of annual dose (i.e., the effective dose equivalent) per unit concentration. Depends on the radionuclide(s), pathway(s), climate, and other factors. A key assumption is that the dose is a linear function of concentration at the geosphere/biosphere interface.
Boiling Regime	One of two divisions (the other being the cooling regime) used to delineate the reactions between the gas, water, and minerals in the rock that occur as the system heats and boiling of the pore water occurs through time.
Borehole	A hole drilled from the surface for purposes of collecting information about an area's geology or hydrology. Sometimes referred to as a drillhole or well bore.
Borosilicate Glass	High-level radioactive waste matrix material in which boron takes the place of the lime used in ordinary glass mixtures.

Boundary Condition	For a model, the establishment of a set condition (set value), often at the geometric edge of the model, for a given variable. An example is using a specified groundwater flux from infiltration as a boundary condition for a flow model.
Breach	An opening in the waste package caused by gradual degradation of the outer and inner barriers that allows the waste to be exposed, and possibly released, to the external environment.
Breakthrough	The time at which the concentration of a substance, usually in groundwater, arrives at a particular point of interest after having been tracked as it moves through space.
Breakthrough Curve	A means of describing transport of radionuclides along a geosphere pathway by constructing a curve that is a cumulative probability distribution. The breakthrough curve calculation includes the effects of all flow modes, flow in rock matrix, flow in fractures, and retardation and determines the expected proportion of the radionuclide mass that has traveled the pathway at any specified time.
Buoyant Convection	Fluid movement, typically in the gas phase, in response to a density gradient in a gravitational field. An example is the rising of air when it becomes less dense because of heating followed by its subsequent fall when it cools and becomes denser.
Burnup	A measure of nuclear-reactor fuel consumption expressed either as the percentage of fuel atoms that have undergone fission or as the amount of energy produced per unit weight of fuel.
Calcite	A crystalline mineral composed of calcium carbonate ($CaCO_3$).
Calibration	The process of comparing the conditions, processes, and parameter values used in a model against actual data points or interpolations (e.g., contour maps) from measurements at or close to the site to ensure that the model is compatible with "reality" to the extent feasible. (2) For tools used for field or lab measurements, the process of taking instrument readings on standards known to produce a certain response to check the accuracy and precision of the instrument.
Canister	The structure surrounding the waste (e.g., high-level radioactive waste immobilized in glass rods) that facilitates handling, storage, transportation, and/or disposal. A metal receptacle with the following purpose: (1) a pour mold for solidified high-level radioactive waste and (2) for spent nuclear fuel, structural support for loose rods, non-fuel components, or containment of radionuclides during postclosure operations.

Capillarity	(1) A phenomenon that results from the force of mutual attraction (cohesion) between water molecules in conjunction with the force of molecular attraction (adhesion) between water and different solid materials. (2) A means by which water will rise in small diameter tubes and, in combination with the effects of gravity, a means of water movement in the unsaturated zone.
Capillary Barrier	A contact in the unsaturated zone between a geologic unit containing relatively small-diameter openings and a unit containing relatively large-diameter openings across which water does not flow.
Capillary Force	In the unsaturated zone, the forces acting on moisture that can be attributed to the attraction between rock grain, or matrix, surfaces and water.
Capillary Pressure	The difference in a fluid pressure at a given point between a nonwetting phase such as air and a wetting phase such as water.
Capillary Suction	A condition in unsaturated rocks in which the attraction of fluids to particle surfaces is stronger than the force of gravity on the fluid.
Carbon Steel	A steel that is tough but malleable and contains a small percentage of carbon. The outer barrier of waste packages is composed of carbon steel.
Carbonate	Any compound formed by the reaction of carbonic acid with either a metal or an organic compound. Any compound containing the carbonate ion.
Carbonation	A chemical process involving the change of concrete and cement into a carbonate.
Carboniferous	Producing, containing, or pertaining to carbon or coal.
Cationic	An atom or group of atoms having a positive charge.
Center For Nuclear Waste Regulatory Analyses	A federally funded research and development center in San Antonio, Texas, sponsored by the Nuclear Regulatory Commission to provide the Nuclear Regulatory Commission with technical assistance for the repository program.
Ceramic Coating	A layer of ceramic material such as alumina that has been applied to a metallic product to protect against extremely high temperatures and corrosion.
Cladding	The metallic outer sheath of a fuel element generally made of stainless steel or a zirconium alloy. It is intended to isolate the fuel element from the external environment.

Clay	A rock or mineral fragment of any composition that is smaller than very fine silt grains, having a diameter less than 0.00016 in. (1/256 mm). A clay mineral is one of a complex and loosely defined group of finely crystalline hydrous silicates formed mainly by weathering or alteration of primary silicate minerals. They are characterized by small particle size and their ability to adsorb large amounts of water or ions on the surface of the particles.
Climate	Weather conditions, including temperature, wind velocity, precipitation, and other factors, that prevail in a region.
Climate Proxies	The physical remains of substances that carry the imprint of past climates.
Climate States	Representations of climate conditions. Three different climate states are used to represent changes in climate over the time periods of interest: present-day dry climate, long-term-average climate (about twice the precipitation of dry climate), and superpluvial climate (about three times the precipitation of dry climate).
Code (Computer)	The set of commands used to solve a mathematical model on a computer.
Codisposal	A packaging method for disposal of radioactive waste in which two types of waste, such as commercial spent nuclear fuel and defense high-level radioactive waste, are combined in disposal containers. Codisposal takes advantage of otherwise unused space in disposal containers and is more cost-effective than other methods to limit the reactivity of individual waste packages.
Coefficient of Multiple Determination	See Section A.2 of this glossary.
Colloid	As applied to radionuclide migration, a colloidal system is a group of large molecules or small particles that have at least one dimension with the size range of 10^{-9} to 10^{-6}m that are suspended in a solvent. Naturally occurring colloids in groundwater arise from clay minerals such as smectites and illites. Colloids that are transported in groundwater can be filtered out of the water in small pore spaces or very narrow fractures because of the large size of the colloids.
Colloid-Facilitated, Radionuclide Transport Model	A model that represents the enhanced transport of radionuclides by particles that are colloids.
Commercial Spent Nuclear Fuel	Commercial nuclear fuel rods that have been removed from reactor use.

Committed Dose Equivalent	The dose equivalent that is committed to specific organs or tissues that will be received from an intake of radioactive material by an individual during the 50 years following the intake.
Committed Effective Dose Equivalent	The sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated and the committed dose equivalent to these organs or tissues.
Complementary Cumulative Distribution Function	See Section A.2 of this glossary.
Component Models	The 16 process models that are run separately and then combined for running in the TSPA-VA RIP computer model.
Concentration Gradient	For a substance dissolved in a solute, the change in concentration of the substance over a distance.
Conceptual Model	A set of qualitative assumptions used to describe a system or subsystem for a given purpose. Assumptions for the model should be compatible with one another and fit the existing data within the context of the given purpose of the model.
Concrete Lining	Part of the reference design in which the large majority of emplacement drifts are lined with precast concrete segments.
Conduction	Transport of heat in static groundwater, controlled by the thermal conductivity of the geologic formation and the contained groundwater and described by a linear law relating heat flux to temperature gradient.
Confidence	See Section A.2 of this glossary.
Confidence Interval	See Section A.2 of this glossary.
Consequence	A measurable outcome of an event or process that, when combined with the probability of occurrence, gives risk.
Conservative Assumption	(1) An assumption that has the effect of maximizing the calculated amount of radionuclides released from the hypothetical repository to the accessible environment. (2) An assumption that uses uncertain inputs and does not attempt to include any potentially beneficial effects.
Conservative Tracer	Substances with no retardation effect. See Tracer.
Continuous Random Variable	See Section A.2 of this glossary.
Continuum Model	A model that represents fluid flow through numerous individual fractures and matrix blocks by approximating them as continuous flow fields.

Convection	(1) Thermally driven groundwater flow or a heat-transfer mechanism for a gas phase. The bulk motion of a flowing fluid (gas or liquid) in the presence of a gravitational field, caused by temperature differences that, in turn, cause different areas of the fluid to have different densities (e.g., warmer is less dense). (2) One of the processes that moves solutes in groundwater. See Transport.
Convolution Integral Method	(1) A computational method used to calculate the radionuclide concentration in the saturated zone as it changes with time. (2) The abstraction method for the saturated zone flow and transport component model of the TSPA-VA RIP computer model.
Cooling Regime	One of two divisions (the other being the boiling regime) used to delineate the reactions between the gas, water, and minerals in the rock, which occur as the system cools after heating and boiling of the pore water occurs through time.
Correlation Coefficient	See Section A.2 of this glossary.
Corrosion	The process of dissolving or wearing away gradually, especially by chemical action.
Corrosion Allowance Material	A material that undergoes relatively uniform corrosion penetration at relatively low and predictable rates in moderately acidic, moderately alkaline, and neutral conditions (see pH). Corrosion allowance material is used as the outer barrier of the two-layer, metallic waste-disposal container and is made of carbon steel.
Corrosion Model (for inner barrier and outer barrier)	A model that includes the time histories of first and subsequent pit and patch penetrations for the waste package layers.
Corrosion Resistant Material	A material that develops a protective film on its surface, creating a high resistance to corrosion. This material, usually the nickel-base alloy, Alloy 22 (ASTM B 575 N06022), is used as the inner barrier of the two-layer waste-disposal container.
Coupling	The ability in a performance assessment to assemble separate analyses so that information can be passed among them to develop an overall analysis of system performance.
Covariance	See Section A.2 of this glossary.
Crevice Corrosion	A type of localized corrosion that forms in splits or cracks.
Critical Event	See Criticality.

Critical Group	With regard to annual dose, the maximally exposed individuals. A group of members of the public whose exposure is reasonably homogeneous and includes individuals receiving the highest dose. The individuals making up the critical group may change with changes in source term and pathway.
Criticality	(1) A condition that would require the original waste form, which is part of the waste package, to be exposed to degradation followed by conditions that would allow concentration of sufficient nuclear fuel, the presence of neutron moderators, the absence of neutron absorbers, and favorable geometry. (2) The condition in which nuclear fuel sustains a chain reaction. It occurs when the number of neutrons present in one generation cycle equals the number generated in the previous cycle. The state is considered critical when a self-sustaining nuclear chain reaction is ongoing.
Critical Population	See Critical Group.
Cumulative Distribution Function	See Section A.2 of this glossary.
Cumulative Probability	See Section A.2 of this glossary.
Cumulative Release	The sum of the radionuclide curies released over a certain period at a specific location.
Curie	A unit of radioactivity equal to 37 billion disintegrations per second.
Darcy's Law	Used in hydrology to describe fluid flow in a porous medium. Darcy's Law states that the fluid velocity is directly proportional to the hydraulic gradient between the two locations.
Data	Facts or figures measured or derived from site characteristics or standard references from which conclusions may be drawn Parameters that have been derived from raw data are sometimes, themselves, considered to be data.
Decay	See Radioactive Decay.
Deep Percolation	Precipitation moving downward, below the plant-root zone, toward storage in subsurface strata.
Defense in Depth	The term used to describe the property of a system of multiple barriers to mitigate uncertainties in conditions, processes, and events by employing barriers that are redundant and independent, such that failure in any one barrier does not result in failure of the entire system.
Defense Spent Nuclear Fuel	See DOE Spent Nuclear Fuel.

Department of Energy, U.S. (DOE)	A Cabinet-level agency of the United States federal government charged with the responsibilities of energy security, national security, and environmental quality.
Design Concept	As mentioned in the Energy and Water Appropriations Act, consists of the subsurface repository layout, the engineered barrier segments, and the waste package.
Desorption	A physical or chemical process by which a substance that has been adsorbed or absorbed by a liquid or solid material is removed from the material.
Deterministic	A single calculation using only a single value for each of the model parameters. A deterministic system is governed by definite rules of evolution leading to cause and effect relationships and predictability. Deterministic calculations do not account for uncertainty in the physical relationships or parameter values.
Diffusion	(1) The spreading or dissemination of a substance. (2) The gradual mixing of the molecules of two or more substances due to random thermal motion.
Diffusive Transport	Movement of solutes due to their concentration gradient. The process in which substances carried in groundwater move through the subsurface by means of diffusion because of a concentration gradient.
Diffusivity	A measure of the rate of heat diffusion. It varies with the nature of the involved atoms, the structure, and changes in temperature.
Dike	A tabular body of igneous rock that cuts across the structure of adjacent rocks or cuts massive rocks. Most dikes are caused by the intrusion of magma. Some dikes occur as columnar structures.
Dimensionality	Modeling in one, two, or three dimensions.
Dimensionality Abstraction	An abstraction in which there is a change in the dimensions of a problem, such as from three dimensional to two dimensional, for modeling purposes. This is done either to simplify the problem or reduce the computational requirements of the problem to implement modeling results in a more efficient or usable form.
Discrete Heat Source	An attribute of drift-scale thermal hydrology models in which the model includes a representation of heat output for discrete waste packages with varying heat outputs depending on the type and amount of waste in the package.

Dispersion (Hydrodynamic Dispersion)	(1) The tendency of a solute (substance dissolved in groundwater) to spread out from the path it is expected to follow if only the bulk motion of the flowing fluid (defection) moved it. The tortuous path the solute follows through openings (pores and fractures) causes part of the dispersion effect in the rock. (2) The macroscopic outcome of the actual movement of individual solute particles through a porous medium. Dispersion causes dilution of solutes, including radionuclides, in groundwater and is usually an important mechanism for spreading contaminants in low flow velocity situations.
Disposal Container	The container barriers or shells, spacing structures or baskets, shielding integral to the container, packing contained within the container, and other absorbent materials designed to be placed internal to the container or immediately surrounding the disposal container (i.e., attached to the outer surface of the container). The disposal container is designed to contain spent nuclear fuel and high-level radioactive waste, but exists only until the outer lid weld is complete and accepted. The disposal container does not include the waste form or the encasing containers or canisters (e.g., high-level radioactive waste pour canisters, DOE spent nuclear fuel co-disposal canisters, multi-purpose canisters of spent nuclear fuel, etc.).
Dissolution	Change from a solid to a liquid state. Dissolving a substance in a solvent.
Distribution	See Section A.2 of this glossary.
Distribution Frequency	See Section A.2 of this glossary.
Disturbed Performance	Performance that is expected for the system if perturbed by disruptive events such as human intrusion, natural phenomena such as volcanism, or nuclear criticality. This is as used in a description of scenario.
Disruptive Event	An unexpected event that, in the case of the repository, includes human intrusion, volcanic activity, seismic activity, and nuclear criticality. Disruptive events have two possible effects: (1) direct release of radioactivity to the surface or (2) alteration of the nominal behavior or the system.
Domain (Model)	(1) The set of elements that a mathematical model describes. (2) Individual process areas, such as the unsaturated zone flow domain.
DOE Spent Nuclear Fuel	Radioactive waste created by defense activities that consists of over 250 different types of spent nuclear fuel and is expected to contribute 2,333 metric tons of heavy metal (MTHM) to the total repository. The major contributor to this waste form is the N-reactor fuel currently stored at the Hanford Site. This waste form also includes 65 MTHM of U.S. Navy spent nuclear fuel.

Dose	The amount of radioactive energy that passes the exchange boundaries of an organism (e.g., skin and mucous membranes) and is taken into living tissues. Dose arises from a combination of the energy imparted by the radiation and the absorption efficiency of the affected organism or tissues. It is expressed in terms of units of the radiation taken in, the body weight or mass impacted, and the time over which the dose occurs or the impact is measured.
Dose Conversion Factor	(1) Any factor used to change an environmental measurement to dose in the appropriate units. (2) The multipliers that convert an amount of radionuclides ingested or inhaled to an estimate of dose.
Dose Equivalent	The product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest. See also Effective Dose Equivalent and Total Effective Dose Equivalent.
Dose Rate	An organism's exposure to radiation over time.
Downgradient	An area toward which water will tend to flow as the result of several factors. The most important factor is the elevation of water levels in wells in that area relative to other areas. The downgradient is the direction in which contaminants released from the potential repository at Yucca Mountain and migrating in the saturated zone might be expected to move. Based on current understanding of the hydraulic gradient below Yucca Mountain, downgradient is toward the south to southeast of the potential repository location in the area within about 5 km.
Drift	From mining terminology, a horizontal underground passage. The nearly horizontal underground passageways from the shaft(s) to the alcoves and rooms. Includes excavations for emplacement (emplacement drifts) and access (access mains).
Drift Scale	The scale of an emplacement drift, or approximately 5 m in diameter.
Drip Shield	A sheet of impermeable material placed above the waste package to prevent seepage water from directly contacting the waste packages.
Dripping Conditions	Assumed for a certain fraction of the waste packages based on water seepage into a drift. The following set of assumptions apply: (1) a small number of the waste packages will be emplaced in drifts with fractures that periodically drip water, and water may drip on a certain fraction of these packages after emplacement; (2) if water drips onto a waste package, it is 100 percent wet from the dripping; and (3) the dripping rate, frequency of drip periods, and water chemistry (especially pH and chloride concentration) will contribute significantly to waste package degradation.

Dry Climate	One of three sets of conditions used to represent climate changes through time. Representative of current climate conditions at Yucca Mountain. See also Long-Term-Average Climate and Superpluvial Climate.
Dual Permeability Conceptual Model	A conceptual model of groundwater flow in which fractures and rock matrix are represented as separate, interacting continua, with no assumption of pressure equilibrium between fractures and rock matrix. This concept allows modeling groundwater flow as occurring mostly in the fractures, with less flow in the rock matrix depending on the degree of connection between the rock matrix and fractures and the capillary pressure gradient. The dual permeability model is one of the conceptual models for groundwater and heat flow for fractured, porous media.
Dual Permeability/Weeps Model	A dual-permeability approximation of the Weeps Model. Also see Dual Permeability Conceptual Model and Weeps Model.
Edge Effects	Conditions at the edges of the repository that are cooler and wetter because heat dissipates more quickly than at the center of the repository.
Effective Dose Equivalent	The sum of the products of the dose equivalent to the organ or tissue and the weighting factors applicable to each of the body organs or tissues that are irradiated.
Effective Porosity	The fraction of a given medium's porosity available for fluid flow and/or solute storage, as in the saturated zone.
Electric Power Research Institute	A nonprofit organization that serves as a research and development consortium serving the entire power industry, from power generation to delivery, to end use products and services. This group has performed an independent performance assessment on the Yucca Mountain site.
Elicitation	See Expert Elicitation.
El Niño	A complex set of changes in the water temperature in the Eastern Pacific equatorial region, producing a warm current. This occurs annually to some degree between October and February, but in some years intensifies and causes unusual storms and destruction of marine life.
Empirical Model	A model whose reliability is based on observation and/or experimental evidence and is not necessarily supported by any established theory or law. Validity or applicability of such an empirical model is normally limited to situations that lie within the range of the data that were used to develop the model.
Emplacement Drift	See Drift.

Energy Policy Act of 1992, Public Law 102-486	Comprehensive energy legislation enacted in 1992. Section 801 of the Act directs the U.S. Environmental Protection Agency (EPA) to contract with the National Academy of Sciences to provide "findings and recommendations on reasonable standards...that would govern the long-term performance of a repository at the Yucca Mountain site." The EPA Administrator is to promulgate public health and safety standards after the receipt of the findings and recommendations of the National Academy of Sciences, and these shall be the only standards applicable to the Yucca Mountain site.
Energy and Water Development Appropriations Act of 1997, Public Law 104-206	Legislation that provided that "no later than September 30, 1998, the Secretary shall provide to the President and to the Congress a Viability Assessment of the Yucca Mountain site. The VA shall include: • the preliminary design concept for the critical elements for the repository and waste package • a total system performance assessment (TSPA), based upon the design concept and the scientific data and analysis available by September 30, 1998, describing the probable behavior of the repository in the Yucca Mountain geological setting relative to the overall system performance standards • a plan and cost estimate for the remaining work required to complete a license application, and • an estimate of the costs to construct and operate the repository in accordance with the design concept."
Engineered Barrier Segments	As mentioned in the 1997 Energy and Water Appropriations Act, include (1) the invert and pedestal systems to support the waste package, (2) any packing or backfill materials that may be used within the drift, (3) and any drip shield that may be placed over or around the waste package.
Engineered Barrier System	The waste packages and the underground facility. The designed, or engineered, components of the disposal system and the waste package.
Engineered Barrier System Transport Model	A computer model that includes the key processes: (1) in-drift thermal hydrology and geochemistry, (2) degradation of the drip shield (if used), (3) degradation of the waste package and cladding, (4) alteration and dissolution of the waste form, (5) degradation of the invert, (6) mobilization of the radionuclides in the waste form, and (7) transport of radionuclides in the drift.
Enrichment	The percentage of the fuel matrix that is fissile.

Environmental Impact Statement (EIS)	A detailed written statement to support a decision to proceed with major Federal actions affecting the quality of the human environment. This is required by the National Environmental Policy Act (NEPA). The environmental impact statement describes: "...the environmental impact of the proposed action; any adverse environmental effects which cannot be avoided should the proposal be implemented; alternatives to the proposed action (although the Nuclear Waste Policy Act, as amended, precludes consideration of certain alternatives); the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity; and any irreversible and irretrievable commitments of resources which would be involved in the proposed action should it be implemented." Preparation of an environmental impact statement requires a public process that includes public meetings, reviews, and comments, as well as agency responses to the public comments. A final environmental impact statement for the Yucca Mountain site is to be published in fiscal year 2000.
Environmental Protection Agency (EPA), U.S.	The agency charged by the Nuclear Waste Policy Act of 1982, and subsequently by the Energy Policy Act of 1992, with promulgating generally applicable standards for protection of the general environment. The proposed repository at Yucca Mountain is overseen by this agency.
Equilibrium	The state of a chemical system in which the phases do not undergo any spontaneous change in properties or proportions with time, a dynamic balance.
Equilibrium Batch Reactor	A concept describing the conditions in a computer model cell in which the value of any given parameter is homogeneous and in equilibrium throughout the cell area. Used when referring to concentration conditions within an individual cell during modeling of engineered barrier transport.
Equivalent Continuum Model	A conceptual model of groundwater and heat flow that is also called a composite porosity model. Key assumptions are that the temperatures and capillary pressures in the rock matrix and fractures are equal. Therefore, the fractures and matrix can be treated as a single composite material, and the hydraulic properties are a combined effect of both fracture and matrix properties.
Evapotranspiration	The combined processes of evaporation and plant transpiration that remove water from the soil and return it to the air.

Event Tree	A structurally tree-like diagram that is useful in representing sequences of events and their possible outcomes. Each node, or branching point, represents an event, such as volcanic activity, and each branch from that node represents one of its possible outcomes. Each branch can continue to branch many times. Each possible pathway along the tree, from beginning to end of a given line of branching, represents a specific scenario.
Events	(1) Occurrences that have a specific starting time and, usually, a duration shorter than the time being simulated in a model. (2) Uncertain occurrences that take place within a short time relative to the time frame of the model.
Expected Behavior	The nominal behavior of the repository system and the geologic barrier in the absence of disruptive events.
Expected Value	See Section A.2 of this glossary.
Expected Value Realization	The single realization derived by sampling all uncertain input parameters in the component models at the expected values of their ranges.
Expert Elicitation	A formal process through which expert judgment is obtained.
Exploratory Studies Facility	An underground laboratory at Yucca Mountain that includes a 7.9-km (4.9-mile) main loop (tunnel), a 2.8-km (1.75-mile) cross-drift, and a research alcove system constructed for performing underground studies during site characterization. The data collected will contribute toward determining the suitability of the Yucca Mountain site. Some or all of the Exploratory Studies Facility may eventually be incorporated into the repository.
External Criticality	A condition in which a critical configuration of fissile material occurs after this material is released from the waste packages. See also Criticality.
Far-Field	With reference to processes, those occurring at the scale of the mountain. The area of the geosphere and biosphere far enough away from the repository that, when numerically modeled, releases from the repository are represented as a homogeneous, single-source effect.
Fast Path	Localized unsaturated zone flow pathways that might have high advective velocities. Fast paths move water, carrying radionuclides, through the unsaturated zone more quickly than if movement were predominantly through the pores of the rock matrix. Fractures are potential fast paths.
Fault (Geologic)	A fracture in rock along which movement of one side relative to the other has occurred.

Features	Physical, chemical, thermal, or temporal characteristics of the site or repository system.
FEHM Computer Code	The Finite Element Heat and Mass transfer computer code that is a process model for unsaturated flow and transport.
Fick's Law	The mass of solute diffusing is proportional to the concentration gradient when a solute in water moves from an area of greater concentration toward an area of lesser concentration by molecular diffusion.
Film Flow	Movement of water as a thin film along a surface.
Finite Difference Computer Code	A commonly used numerical method for solving flow problems. An approximating technique in which algebraic equations are used for approximating the partial differential equations that comprise mathematical models in order to produce a form of the problem that can be solved on a computer. For this type of approximation the real world area being modeled is formed into a grid with cubical or rectangular blocks. Values for parameters, such as head, are computed at the grid nodes with the same value also being the average for the area surrounding the node.
Finite Element Computer Code	A commonly used numerical method for solving flow problems. An approximating technique in which algebraic equations are used for approximating the partial differential equations that comprise mathematical models in order to produce a form of the problem that can be solved on a computer. For this type of approximation the real world area being model is formed into a grid with irregularly shaped blocks. This method provides an advantage in handling irregularly shaped boundaries, internal features such as faults, and simulation of point sources (of contamination), seepage faces, and moving water table elevations. Values for parameters are frequently calculated at nodes for convenience, but are defined everywhere in the blocks by means of interpolation functions.
Fissile	Sometimes used as a synonym for fissionable (see Fission). Fissile material can undergo fission with neutrons of any energy, including thermal, or slow, neutrons. The three primary materials in this category are uranium-233, uranium-235, and plutonium-239. Fissionable nuclides require fast neutrons to undergo fissions.
Fissile Material	See Fissile.
Fission	The splitting of a nucleus into at least two other nuclei, resulting in the release of two or three neutrons and a relatively large amount of energy.

Fission Products	A complex mixture of nuclides produced by the process of fission that includes radioactive (and some nonradioactive nuclides) as well as the daughter products of the radioactive decay of these nuclides, which can result in more than 200 isotopes.
Flow	The movement of a fluid such as air or water. Flow and transport are groundwater processes that can move potential contaminants; it usually means flow based on Darcy's law.
Flow Pathway	The subsurface course that a water molecule or solute (including radionuclides) would follow in a given groundwater velocity field governed principally by the hydraulic gradient.
Flux	The rate of transfer of fluid, particles, or energy passing through a unit area per unit time. For water, also known as specific discharge.
Fractures	Breaks in rocks caused by the stresses that cause folding and faulting. A fracture along which there has been displacement of the sides relative to one another is called a fault. A fracture along which no appreciable movement has occurred is called a joint. Fractures may act as fast paths for groundwater movement.
Fracture Aperture	(1) The space that separates the sides of a fracture. (2) The measured width of the space separating the sides of a fracture.
Fracture Permeability	The capacity of a rock to transmit fluid that is related to fractures in the rock.
Fracture-Matrix Exchange Coefficient	(1) A multiplier used in unsaturated groundwater flow simulations that alters the geometric conductance between fracture and matrix elements to account for reduced wetting and contact area. (2) A coefficient that assists in capturing the effect of groundwater being distributed unevenly over fracture surfaces as moves through fractured rock.
Frequency Distribution	See Section A.2 of this glossary.
Fuel Assembly	A number of fuel rods held together by plates and separated by spacers, used in a reactor. This assembly is sometimes called a fuel bundle.
Fuel Matrix	The physical form and composition of the substance that holds the fissile material.
Fugacity	A parameter that measures the chemical potential of a real gas in the same way that partial pressure measures the free energy of an ideal gas.
Galvanic	Pertaining to an electrochemical process in which electron flow is produced between two dissimilar metals when they are immersed in an electrolyte solution and placed in contact or are electrically connected. The electron flow results from the difference in electrical potential of the metals.

Galvanic Corrosion	Electrochemical corrosion (eating into a substance) caused by the flow of electricity that occurs when two dissimilar metals, with differing electrical potentials, are near each other in the presence of a conductor such as water with solutes in it.
Gaseous Diffusion	The selective transfer of gas by molecular diffusion through microporous barriers. Used to refer to the mechanism for movement of gas through concrete and rock and for movement of gas out of the waste package by means not involving water.
GENII	A deterministic computer software code that evaluates dose from the migration of radionuclides introduced into the accessible environment, or biosphere, that may eventually affect humans through ingestion, inhalation, or direct radiation. It is used to develop biosphere dose conversion factors.
GENII-S	A quasi-stochastic computer software code that can create distributions and sample them and is run in conjunction with GENII for biosphere modeling.
Geochemical	The distribution and amounts of the chemical elements in minerals, ores, rocks, soils, water, and the atmosphere, and the circulation of the elements in nature on the basis of their properties.
Geochemistry	The study of the abundance of the elements and atomic species (isotopes) in the earth. Geochemistry, or geochemical study looks at systems related to chemicals arising from natural rock, soil, soil processes such as microbe activity, and gases, especially as they interact with man-made materials from the repository system. In the broad sense, all parts of geology that involve chemical changes.
Geologic-Framework Model	A nonmathematical model of the geologic system.
Geologic Repository	A system for disposing of radioactive waste in excavated geologic media, including surface and subsurface areas of operation, and the adjacent part of the geologic setting that provides isolation of the radioactive waste.
Geologic Time	The period of time over which the earth has existed. The time scale over which geologic processes produce change. In general discussion, the term geologic time implies very long periods of time such as tens of thousands of years, hundreds of thousands of years, or millions of years.
Geosphere	The combination of the earth's rock, water, and air layers (spheres).
Glass	See High-Level Radioactive Waste Glass.

Goethite	An iron oxide mineral that is yellowish, reddish, or brownish black. It is the most common constituent of many forms of natural rust or of limonite.
Gradient	The change in value of a quantity per unit distance in a specified direction.
Groundwater	Water contained in pores or fractures in either the unsaturated or saturated zones below ground level.
Groundwater Flux	The rate of groundwater flow through a unit area of the aquifer. Means the same as specific discharge.
Groundwater Travel Time	The time required for a unit volume of groundwater to travel between two locations. The travel time is the length of the flow path divided by the velocity, where velocity is the average groundwater flux divided by the effective porosity along the flow path. If discrete segments of the flow path have different hydrologic properties, the total travel time will be the sum of the travel times for each discrete segment.
Handling Container	The container in which the fuel matrix and cladding are placed. If the waste form is solidified, this is called a pour container. In some cases, this is the only container for storage, handling, and transportation prior to disposal.
Heavy Metal	All uranium, plutonium, and thorium used in a nuclear reactor.
Herbivore	An organism that feeds on plants, especially an animal whose diet is exclusively plants.
Heterogeneity	The condition of being composed of parts or elements of different kinds. A condition in which the value of a parameter such as porosity, which is an attribute of an entity of interest such as the tuff rock containing the repository, varies over the space an entity occupies, such as the area around the repository, or with the passage of time.
High-Level Radioactive Waste	(1) The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing, and any solid material derived from such liquid waste that contains fission products in sufficient concentrations (2) Other highly radioactive material that the Nuclear Regulatory Commission, consistent with existing law, determines by rule requires permanent isolation.
High-Level Waste	See High-Level Radioactive Waste.
High-Level Radioactive Waste Glass	The waste form of defense high-level radioactive waste in which the radioactive waste is mixed with borosilicate glass.
Histogram	See Section A.2 of this glossary.

Homogeneous	Consisting of or composed of similar elements or ingredients.
Host Rock	The rock unit in which the repository will be located. For the repository at Yucca Mountain, the host rock would be the middle portion of the of the Topopah Spring tuff formation of the Paintbrush Group. See also tuff.
Hydraulic Conductivity	A measure of the ability to transmit water through a permeable medium. A number that describes the rate at which water can move through a permeable medium. The hydraulic conductivity depends on the size and arrangement of water-transmitting openings such as pores and fractures, the dynamic characteristics of the water such as density and viscosity, and the strength of the gravitational field.
Hydraulic Gradient	The change in the height of water levels with respect to the distance between two locations.
Hydrodynamic Dispersion	See Dispersion.
Hydrogeology	A study that encompasses the interrelationships of geologic materials and processes involving water.
Hydrologic	Pertaining to the properties, distribution, and circulation of water on the surface of the land, in the soil and underlying rocks, and in the atmosphere.
Hydrology	(1) The study of water characteristics, especially the movement of water. (2) The study of water, involving aspects of geology, oceanography, and meteorology.
Hydrostratigraphy	A stratigraphic classification of layered rocks based on rock characteristics and the hydrologic, or water-conducting, properties of the units.
Human Intrusion	The inadvertent disturbance of a disposal system by humans that could result in release of radioactive waste. Subpart B of 40 CFR 191 requires that performance assessments consider the possibility of human intrusion.
Igneous	(1) A type of rock that has formed from a molten, or partially molten, material. (2) A type of activity related to the formation and movement of molten rock either in subsurface (plutonic) or on the surface (volcanic).
Imbibition	The absorption of a fluid, usually water, by porous rock (or other porous material) under the force of capillary attraction and without pressure.
Incolloy 625	Under past reference design specifications, the corrosion resistant inner layer of the two layer metallic disposal container. The inner layer material for calculations related to disruptive scenarios.

Infiltration	The process of water entering the soil at the ground surface and the ensuing movement downward when the water input at the soil surface is adequate. Infiltration becomes percolation when water has moved below the depth at which it can be removed (to return to the atmosphere) by evaporation or evapotranspiration.
Infiltration Flux	Volumetric infiltration rate per unit area.
Infiltration Rate	See Infiltration Flux.
Inner Barrier	An inner layer of the two-layer metallic disposal container. The inner layer is constructed with corrosion-resistant material such as Alloy 22 (ASTM B575 N06022), a nickel-base, high- performance material. See also Corrosion Resistant Material.
Inner Canisters	High-level radioactive waste canisters placed within the overpack.
In Situ	In its natural position or place. The phrase distinguishes in-place experiments, conducted in the field or underground facility, from those conducted in the laboratory.
Integral-Finite-Difference Computer Code	A commonly used numerical method for solving flow problems. An approximating technique in which algebraic equations are used for approximating the partial differential equations that comprise mathematical models in order to produce a form of the problem that can be solved on a computer. Similar in capability to a finite element code in that it can handle irregularly shaped areas well. See Finite Element Computer Code.
Inventory	The amount of radioactive elements in a fuel, usually stated in curies per metric ton of heavy metal. Also termed radionuclide inventory.
Invert	A construction associated with the precast concrete structure for the purpose of providing a level drift floor and enabling transporting and support of the waste package.
Ion	(1) An atom that contains excess electrons or is deficient in electrons, causing it to be chemically active. (2) An electron not associated with a nucleus.
Ionizing Radiation	(1) Alpha particles, beta particles, gamma rays, x-rays, neutrons, high-speed electrons, high-speed protons, and other particles capable of producing ions. (2) Any radiation capable of displacing electrons from an atom or molecule, thereby producing ions.
Ionic Strength	A measure of the level of electrical force in an electrolytic solution.
Irradiated Fuel	Burned fuel. See also Burnup.
Isothermal	Pertaining to constant temperature.

Isotope	One of two or more atomic nuclei with the same number of protons (i.e., the same atomic number) but with a different number of neutrons (i.e., a different atomic weight). For example, uranium-235 and uranium-238 are both isotopes of uranium.
Isotropy	The condition wherein all significant physical properties are equal when measured in any direction or along any axes. See also Anisotropy.
Iterative	Conditions or results that are repeated in an analysis. The processes in which analysts rerun calculations or refine models as new data are gathered or new insights occur.
ITOUGH2 Computer Code	A computer code that estimates hydrogeologic model parameters for the numerical simulator TOUGH2.
J-13 Water	The groundwater taken from Wellbore J13. The chemical composition of this water is used as the standard for Yucca Mountain ambient groundwater composition for modeling purposes.
Joint	A fracture in rock, usually more or less vertical to bedding, along which no appreciable movement has occurred.
Juvenile Failure	Premature failure of a waste package because of material imperfections or damage by rockfall during emplacement.
Key Technical Issues	Issues important for assessing the long-term safety of a potential Yucca Mountain repository, as defined by the Nuclear Regulatory Commission (NRC). The issues are (1) Support Revision of the U.S. Environmental Protection Agency Standard/NRC Rule Making; (2) TSPA and Technical Integration; (3) Igneous Activity; (4) Unsaturated and Saturated Flow Under Isothermal Conditions; (5) Thermal Effects on Flow; (6) Container Life and Source Term; (7) Structural Deformation and Seismicity; (8) Evolution of Near-Field Environment; (9) Radionuclide Transport; (10) Repository Design and Thermal-Mechanical Effects.
Kinetic	Of or due to motion.
Latin Hypercube Sampling	A sampling technique that divides the cumulative distribution function into intervals of equal probability and then samples from each interval.
License Application	An application to the Nuclear Regulatory Commission for a license to construct a repository.
Line Loading Repository Design	A waste emplacement design in which waste containers are spaced very closely along the drift, with emplacement drifts relatively far apart.

Lithophysal	Pertaining to tuff units with lithophysae, voids having concentric shells of finely crystalline alkali feldspar, quartz, and other materials that were formed due to entrapped gas that later escaped.
Lithosphere	The earth's crust, as distinguished from the atmosphere or hydrosphere, and as distinguished from the deeper portion of the earth underlying the crust.
Localized Corrosion	A type of corrosion induced by local variations in electrochemical potential on a microscale over small regions. Variations in electrochemical potential may be caused by localized irregularities in the structure and composition of usually protective passive films on metal surfaces and in the electrolyte composition of the solution that contacts the metal. See Pitting Corrosion and Crevice Corrosion.
Log Normal Distribution	A distribution of a random variable X such that the natural logarithm of X is normally distributed.
Long-Term-Average Climate	One of three sets of conditions used to represent climate changes through time. Representative of the expected typical climate conditions at Yucca Mountain, with precipitation twice that of the present-day climate. See also Dry Climate and Superpluvial Climate.
Lookup Table	A multidimensional table containing columns of data representing relationships between parameters in the table. A lookup table is a convenient way to represent and implement functional relationships between parameters considered in the model.
Longitudinal Dispersion	(1) Dispersion of a solute moving in groundwater in the same direction as the groundwater flow path. (2) Spreading of a solute in the direction of bulk flow.
Magma	Molten or partially molten rock material that is naturally occurring and is generated within the earth.
Mass Balance	The procedure of accounting for conservation of mass, such as the mass of radionuclides released from waste packages, in real world processes or in models of real world processes.
Mathematical Model	A mathematical description of a conceptual model.
Matrix	Tuff rock material and its pore space exclusive of fractures. As applied to Yucca Mountain tuff, the groundmass of an igneous rock that contains larger crystals.

Matrix Diffusion	As used in TSPA-VA conceptual models, the process by which molecular or ionic solutes, such as radionuclides in groundwater, move from areas of higher concentration to areas of lower concentration. This movement is through the pore spaces of the rock material as opposed to movement through the fractures.
Matrix Permeability	The capacity of the matrix to transmit fluid.
Mean (Arithmetic)	See Section A.2 of this glossary.
Mechanistic Analysis	An analysis of processes that is based on the well established fundamentals of the processes considered, such as: thermodynamics, reaction kinetics, mass transfer laws, heat transfer laws, etc. This is as opposed to empirical analysis, which is based on a model that has been developed from the numerical value of data taken from tests or measurements of the model.
Median	A value such that half of the observations are less than that value and half are greater than the value.
Meteorological	Of, or relating to meteorology, or to weather and other atmospheric phenomena.
Metric Ton Heavy Metal (MTHM)	A metric ton is a unit of mass equal to 1,000 kg (2,205 lb). Heavy metals are those with atomic masses greater than 230. Examples include thorium, uranium, plutonium, and neptunium. When used in the Civilian Radioactive Waste Management Program, the term usually pertains to heavy metals in spent nuclear fuel in scientific text. In this document, MTHM is equal to MTU (metric tons of uranium).
Metric Ton of Uranium (MTU)	A metric ton, which is 1,000 kg, or 2,205 lb, of uranium in scientific text.
Microbe	An organism too small to be viewed with the unaided eye. Examples of microbes are bacteria, protozoa, and some fungi and algae.
Microbially Influenced Corrosion	Corrosion of the waste package that is enhanced by the activity of microbes.
Microbiologically Influenced Corrosion	See Microbially Influenced Corrosion.
Migration	Radionuclide movement from one location to another within the engineered barrier system or the environment.
Mild Steel	See Carbon Steel.
Mineral Assemblage	Minerals that compose a rock, especially an igneous or metamorphic rock. The term includes the different kinds and relative abundance of minerals but excludes the texture and fabric of the rock.

Mineralogical	Of or relating to the chemical and physical properties of minerals, their occurrence, and classification.
Mobile Radionuclides	Radionuclides that can move within a water system with little or no retardation.
Mobilization	The process of breaking down the waste form and releasing radionuclides. After its initial mobilization a radionuclide can be removed from transport by being precipitated or adsorbed and later become remobilized in a cycle of changes that can be repeated many times.
Model	A depiction of a system, phenomenon, or process including any hypotheses required to describe the system or explain the phenomenon or process.
Molal	Of a solution, containing one mole of solute per one kilogram of solvent.
Mole	The fundamental SI unit used to measure the amount of a substance. Avagadro's number of particles (6.023×10^{23}).
Monte Carlo Uncertainty Analysis	See Section A.2 of this glossary.
Mountain Scale	(1) Similar to far-field for processes that are related to the area of the geosphere and biosphere far enough away from the repository that, when numerically modeled, show that releases from the repository are represented as a homogeneous, single source term. The effects of individual, small-scale components such as individual waste packages are not modeled because they are considerably smaller than the scale of the model. (2) A scale of hundreds of meters, or even kilometers, as opposed to tens of meters.
National Academy of Sciences	A congressionally chartered, private, nonprofit, self-perpetuating organization of scientists devoted to the expansion of science and its use for the general welfare. This organization is mandated to advise the Federal Government on scientific and technical matters. Section 801 of the Energy Policy Act of 1992 directed the U.S. Environmental Protection Agency to contract with the National Academy of Sciences to provide, "findings and recommendations on reasonable standards...that would govern the long-term performance of a repository at the Yucca Mountain site."
National Research Council	The working arm of the National Academy of Sciences and the National Academy of Engineering that carries out most of the studies done on behalf of the academies. Most of the studies are done in response to specific questions presented by federal agencies or Congress.

Natural Analogs	Natural geologic systems that parallel situations that can develop in man-made systems, in which the formation and transport of minerals over hundreds of thousands and millions of years can be studied directly. An example of natural analog is the natural reactor studied at the Oklo uranium deposit in Gabon, Africa, which can be used as a source of analog data for conceptual models of criticality.
Near Field	The area and conditions within the repository including the drifts and waste packages and the rock immediately surrounding the drifts. The region around the repository where the natural hydrogeologic system has been significantly impacted by the excavation of the repository and the emplacement of waste.
Near-Field Geochemical Environment Model	A model that focuses on major-element geochemistry within the potential emplacement drifts. The boundary of the model domain is defined as the drift wall. This model includes coupling to thermohydrologic processes.
Net Infiltration	The water that has infiltrated down from the soil zone or exposed rock surface to a depth below which it cannot be removed by evapotranspiration. The amount of water that is net infiltration is the total infiltration at the surface minus water lost to evaporation and plant transpiration.
Neutron Absorber	A material such as boron or gadolinium that is placed in a radioactive waste package and that absorbs neutrons to reduce ionizing radiation and to help reduce the likelihood of criticality.
Node	A junction point in a network.
Nominal Case	The case, or conceptual model, representing the expected conditions of the disposal system as perturbed only by the presence of the repository, in the absence of disruptive events.
Nominal Conditions	The site conditions, including features and processes, which are expected, based on current site knowledge.
Nominal Behavior	(1) Expected behavior of the system as perturbed only by the presence of the repository. (2) Behavior of the system in the absence of disruptive events.
Nominal Features, Events, and Processes	Those features, events and processes expected, given the site conditions as described from current site characterization information.
Nonequilibrium Thermodynamics	The study of heat flow systems that have not stabilized (i.e., are not in equilibrium).
Nuclear Chain Reaction	A process in which some of the neutrons released in one fission event cause other fissions.

Nuclear Regulatory Commission (NRC)	Promulgates technical regulations that are consistent with standards established by the U.S. Environmental Protection Agency (EPA) and considers license applications from the U.S. Department of Energy for a proposed repository. It determines, with reasonable assurance, whether EPA standards can be met. It also has the continuing regulatory responsibility to oversee repository operation. NRC was formed by the Atomic Energy Commission with the 1974 Energy Reorganization Act, Public Law 93-438.
Nuclear Regulatory Commission Radioactive Waste Program Annual Progress Report	A status report made each fiscal year that documents the technical work performed on 10 key technical issues that are most important to performance of the proposed geologic repository at Yucca Mountain.
Nuclear Waste Policy (42 USC 10101 et seq.)	The federal statute enacted in 1982 that established the Office of Civilian Radioactive Waste Management (OCRWM) and defined its mission to develop a federal system for the management and geologic disposal of commercial spent nuclear fuel and other high-level radioactive wastes. The Act also: (i) specified other federal responsibilities for nuclear waste management, (ii) established the Nuclear Waste Fund to cover the cost of geologic disposal, (iii) authorized interim storage under certain circumstances, and (iv) defined interactions between Federal agencies and the states, local governments, and Indian tribes. The act was substantially amended in 1987 and 1992.
Nuclear Waste Policy Amendments Act of 1987, Public Law 100-203	Legislation that amended the Nuclear Waste Policy Act to: (i) limit repository site characterization activities to Yucca Mountain, Nevada, (ii) establish the Office of the Nuclear Waste Negotiator to seek a state or Indian tribe willing to host a repository or monitored retrievable storage facility, (iii) create the Nuclear Waste Technical Review Board, and (iv) increase state and local government participation in the waste management program.
Nuclear Waste Technical Review Board	An independent body established within the executive branch, created by the Nuclear Waste Policy Amendments Act of 1987 to evaluate the technical and scientific validity of activities undertaken by the U.S. Department of Energy, including site characterization activities and activities relating to the packaging or transportation of high-level radioactive waste or spent nuclear fuel. Members of this Board are appointed by the President from a list composed by the National Academy of Sciences.
NUFT Computer Code	A computer code that simulates three-dimensional flow of groundwater, heat, and contaminants in unsaturated and saturated porous and fractured media. It is named for Non-isothermal Unsaturated Flow and Transport and is used for drift scale, thermal-hydrologic calculations.

Numerical Model	An approximate representation of a mathematical model that is constructed using a numerical description method, such as finite volumes, finite differences, or finite elements. A numerical model is typically represented by a series of program statements that are executed on a computer.
Office of Civilian Radioactive Waste Management (OCRWM)	A U.S. Department of Energy office created by the Nuclear Waste Policy Act of 1982 to implement the responsibilities assigned by the Act.
One-Dimensional Model	A model that represents physical conditions and/or processes by a vertical column composed of a stack of single grid cells or by a horizontal row of single grid cells.
Order of Magnitude	A range of numbers extending from some value to ten times that value.
Outer Barrier	The outer layer of the two-layer metallic disposal container. It consists of carbon steel, which is a corrosion allowance material.
Outer Barrier and Inner Barrier Corrosion Models	See Corrosion Models.
Outer Barrier Corrosion Model	See Outer Barrier and Inner Barrier Corrosion Models.
Overburden	Geologic material of any nature, consolidated or unconsolidated, that overlies a deposit of useful materials. As used by the Yucca Mountain Site Characterization Project, this is geologic material overlying the mined repository horizon.
Oxidation	(1) A chemical reaction, such as the rusting of iron, that increases the oxygen content of a substance. (2) A reaction in which the valence of an element or compound is increased as a result of losing electrons.
Oxidation State	For an ion, expressed as a positive or negative number representing the ionic or effective charge.
Oxidize	(1) To increase the oxygen content of a substance. (2) To increase the valence of an element or compound as a result of losing electrons.
Paleoclimates	The climate of a past interval of geologic time.
Parameter	Data, or values, that are input to computer codes for a TSPA calculation.
Passive Institutional Control	From 40 CFR 191, methods of preserving information about the location, design and contents of the repository system. These include permanent markers placed around the disposal site area, public records and archives, government ownership, and regulations controlling use of land.

Patch	For corrosion modeling, one of two geometries for an opening in a waste package layer created by corrosion (the other geometry is a pit). A patch is generally wider than it is deep.
Pathway	A potential route by which radionuclides might reach the accessible environment and pose a threat to humans.
Peer Review Panel	A panel of individuals—independent of those who performed the TSPA-VA but who have technical expertise at least equivalent to those who performed the original work—who produce a documented critical review of the work.
Percentile	See Section A.2 of this glossary.
Perched Water	A saturated condition that is not continuous with the water table, because there is an impervious or semipervious layer underlying the perched zone or a fault zone that creates a barrier to water movement and perches water.
Percolation	The passage of a liquid through a porous substance. In rock or soil it is the movement of water through the interstices and pores under hydrostatic pressure and the influence of gravity. The downward or lateral flow of water that becomes net infiltration in the unsaturated zone.
Percolation Flux	Volumetric percolation rate per unit area. The flux anywhere below the root zone of plants and is no longer susceptible to removal back into the atmosphere by evapotranspiration.
Percolation Rate	See percolation flux.
Performance Assessment	An analysis that predicts the behavior of a system or system component under a given set of constant and/or transient conditions. Performance assessments will include estimates of the effects of uncertainties in data and modeling. See TSPA.
Permeability	In general terms, the capacity of a medium like rock, sediment, or soil to transmit liquid or gas. Permeability depends on the substance transmitted (oil, air, water, etc.) and on the size and shape of the pores, joints, and fractures in the medium and the manner in which they are interconnected. "Hydraulic conductivity" has replaced "permeability" in technical discussions relating to groundwater. See also Relative Permeability.
pH	A number indicating the acidity or alkalinity of a solution. A pH of 7 indicates a neutral solution. Lower pH values indicate more acidic solutions while higher pH values indicate alkaline solutions.

Phase	A physically distinct portion of matter, such as the aqueous, gas, or solid phase.
Phase Equilibria	The relationships between phases of a substance undergoing a phase change, such as from solid to liquid, under various conditions of temperature and pressure.
Phase Stability	A measure of the ability of matter to remain in a given phase.
Pit	For corrosion modeling, one of two geometries for an opening in a waste package layer created by corrosion (the other geometry is a patch). A pit is generally deeper than it is wide.
Pitting Corrosion	A type of localized corrosion that forms in indentations called pits.
Pitting Factor	A factor that is used to measure local variations of general, or uniform, corrosion penetration from corrosion allowance materials such as carbon steel.
Playa	The shallow central basin of a desert plain in which water gathers after a rain and then evaporates.
Plume	A measurable discharge of a contaminant, such as radionuclides, from a point of origin. The contaminants are usually moving in groundwater, and the plume may be defined by chemical concentration gradients.
Pluvial	(1) In climatology, relating to former periods of abundant rains, especially in reference to glacial periods. (2) In geology, said of a geologic episode, change, process, deposit, or feature caused by the action or effects of rain.
Point Loading Thermal Design	An emplacement drift design in which commercial spent nuclear fuel waste packages are spaced away from each other along the drift using emplacement drift spacing similar to the commercial spent nuclear fuel-package spacing.
Pore Fluid	The water and any material it is carrying that exist in the pore spaces of the rock matrix.
Pore Waters	Interstitial water, or subsurface water in the pores in rock or soil.
Porosity	The ratio of openings, or voids, to the total volume of a soil or rock expressed as a decimal fraction or as a percentage. See also Effective Porosity.
Pour Canister	A metallic canister into which high-level radioactive waste mixed with molten glass-making materials is poured. The material cools and solidifies in the pour canister.

Precipitate	A substance that separates as solid particles from a liquid as a result of physical or chemical changes.
Precipitation	(1) The process of depositing a substance from a solution, by the action of gravity or by a chemical reaction. (2) Any form of water particles, such as frozen water in snow or ice crystals, or liquid water in raindrops or drizzle, that fall from clouds in the atmosphere and reaches the earth's surface. (3) An amount of water that has fallen at a given point over a specified period of time, measured by a rain gauge.
Probabilistic	(1) Based on or subject to probability. (2) Involving a variate, such as temperature or porosity. At each instance of time, the variate may take on any of the values of a specified set with a certain probability. Data from a probabilistic process is an ordered set of observations, each of which is one item from a probability distribution.
Probabilistic Risk Assessment	(1) A systematic process of identifying and quantifying the consequences of scenarios that could cause a release of radioactive materials to the environment. (2) Using predictable behavior to define the performance of natural, geologic, human, and engineered systems for thousands of years into the future using probability distributions (see Section A.2 of this glossary).
Probability	See Section A.2 of this glossary.
Probability Density Function	See Section A.2 of this glossary.
Probability Distribution	See Section A.2 of this glossary.
Probability Model	A model that quantifies uncertainties in the model parameters and predicts the likelihood of the scenarios used for the model.
Probable Behavior	A combination of the concept of predicted future behavior of the various system components with the uncertainty associated with the prediction.
Process Model	A depiction or representation of a process along with any hypotheses required to describe or to explain the process.
Processes	Phenomena and activities that have gradual, continuous interactions with the system being modeled.
Pyroclastic Flow	A flow of detrital volcanic materials that have been explosively ejected from a volcanic vent. The flow is generally a dense cloud of incandescent volcanic glass, in a semimolten or viscous state, that solidifies into rock. The rock that results is chiefly a fine-grained rhyolitic tuff formed of glass shards that may be welded or nonwelded.
Quantitative	A variable that is expressed numerically.

Quality Factor	The modifying factor that is used to derive dose equivalent from absorbed dose.
Quasi-Static Thermodynamic Processes	Reversible processes resulting in a change to system or body.
Quasi-Transient	Describing the diffusive mass transport model. This means the solution used in the model incorporates steady-state diffusive mass transfer through the perforations of the failed waste container. This is combined with transient mass transfer through the spherical shell of the invert surrounding the waste container. The quasi-transient mass transfer model is used to calculate diffusive release of radionuclides at the engineered barrier system edge.
Rad	The unit of measure for the absorbed dose of radiation. Rad is short for radiation absorbed dose.
Radiation	Ionizing radiation.
Radioactive Decay	The process in which one radionuclide spontaneously transforms into one or more different radionuclides, which are called daughter radionuclides.
Radioactivity	The property possessed by some elements (i.e., uranium) of spontaneously emitting alpha, beta, or gamma rays by the disintegration of atomic nuclei.
Radiocolloid	Colloids, or colloidal systems, containing radionuclides.
Radiolysis	Chemical decomposition by the action of radiation.
Radionuclide	Radioactive type of atom with an unstable nucleus that spontaneously decays, usually emitting ionizing radiation in the process. Radioactive elements characterized by their atomic mass and number.
Random Variable	See Section A.2 of this glossary.
Range (Statistics)	See Section A.2 of this glossary.
REACT Computer Code	The reaction mass transfer code.
Reaction Kinetics	The study of the rates and mechanisms of chemical reactions.
Reaction Rate	The rate at which a chemical reaction takes place.
Realization	A complete calculation using a randomly selected value. Many of these calculations are done in a Monte Carlo analysis.
Recharge	The movement of water from the unsaturated zone to the saturated zone.

Reducing Conditions	With regard to criticality, the important aspect of reducing conditions is that they reduce the oxidation state of materials (deoxidize), and the material that is reduced becomes less soluble. Radionuclides being transported in groundwater can precipitate out and collect in an area of reducing conditions. With regard to corrosion, reducing conditions slow corrosion, because oxygen is less available, or not available, to combine with the iron and form rust.
Reference Person	With regard to dose, a hypothetical collection of human physical and physiological characteristics arrived at by international consensus. This collection may be used by researchers to relate biological damage to a stimulus such as radiation exposure. The reference adult person lives 20 km (12 miles) from Yucca Mountain and will be defined using a survey of the existing population.
Reflux Water	Water that is vaporized near waste packages, migrates to cooler areas, condenses, and then flows back toward the waste packages.
Regression Analysis	See Section A.2 of this glossary.
Relative Permeability	The permeability of rock material to a given substance compared to the absolute (total) permeability of the rock. The term is usually used to signify the permeability to one fluid when two or more fluids are present in the rock.
rem	The unit of a dose equivalent from ionizing radiation to the human body. It is used to measure the amount of radiation to which a person has been exposed) (rem means roentgen equivalent man).
Repository Layout	The host rock, depth, and areal extent of the repository facility, drift size and spacing, mechanical support system, thermal load, and ventilation system used during the operational phase of the facility. This is as mentioned in the Energy and Water Appropriations Act of 1997.
Repository Safety Strategy	A document used to assist management in prioritizing testing and analysis activities to focus on the most important issues in postclosure safety. Identification of the important issues allows resource use (e.g., sampling and testing activities) to be focused on gathering information that will reduce the uncertainty in parameters and processes related to the key issues. Key elements of the document include the following: (1) Limited water contacting waste packages (2) Long waste package lifetime (3) Low rate of release of radionuclides from breached waste packages (4) Radionuclide concentration reduction during transport from the waste packages

Retardation	Slowing or stopping of radionuclide movement in groundwater by mechanisms that include sorption of radionuclides, diffusion into rock matrix pores and microfractures, and trapping of large colloidal molecules in small pore spaces or dead ends of microfractures.
RIP Computer Program	RIP is an initialism for repository integration program, the executive TSPA "driver" program. An integrating software code into which simplified analytical expressions, or callable subroutines describing the behavior of the different components, can be placed. RIP sequentially advances through time while keeping track of the changes in environments and the fate of the radioactive constituents within the engineered and natural barriers.
Risk	The probability that an undesirable event will occur multiplied by the consequences of the undesirable event.
Risk Assessment	An evaluation of potential consequences or hazards that might be the outcome of an action. This assessment focuses on potential negative impacts on human health or the environment.
Rock Matrix	See Matrix.
Salt Deposit Effect	(1) Potential buildup of salt scales on the waste package surface from water dripping onto the waste package while its surface is at elevated temperatures. (2) The development of potentially aggressive conditions to the waste package corrosion degradation under and around the salt deposits by providing a wetter environment than the surroundings and causing concentration of aggressive species in the local salt solution.
Saturated Zone	The region below the water table where rock pores and fractures are completely saturated with groundwater.
Scenario	A well-defined, connected sequence of features, events and processes that can be thought of as an outline of a possible future condition of the repository system. Scenarios can be undisturbed, in which case the performance would be expected, or nominal, behavior for the system. The scenario can also be disturbed, if altered by disruptive events such as human intrusion, natural phenomena such as volcanism, or nuclear criticality.
Secondary Phase	Occurs when spent nuclear fuel is contacted by water and dissolves, forming uranyl minerals. The major secondary phase minerals are schoepite, uranophane, Na-boltwoodite, and soddyite.
Seepage	The inflow of groundwater moving in fractures or pore spaces of permeable rock to an open space in the rock such as a drift. Specifically, the amount of percolation flux that enters the drift in a given time period. An important factor in waste package degradation and mobilization and migration of radionuclides out of the repository.

Seepage Fraction	The fraction of the total number of waste packages that is contacted by drips from seepage into the drifts.
Seismic	Pertaining to, characteristic of, or produced by earthquakes or earth vibrations.
Sensitivity Study (Analysis)	An analytic or numerical technique for examining the effects of varying specified parameters when a model run is performed. Shows the effects that changes in various parameters have on model outcomes and can illustrate which parameters have a greater impact on the predicted behavior of the system being modeled. Also, called sensitivity analysis because it shows the sensitivity of the consequences (e.g., radionuclide release) to uncertain parameters (e.g., the infiltration rate that results from precipitation).
Simulation	The generation of a sample set by selecting a parameter value from each input distribution and calculating the consequences for the sample set. See also Realization.
Single Heater Test	A field test in the Exploratory Studies Facility that uses a single heated element emplaced directly into Yucca Mountain tuff (Topopah Spring Middle Nonlithophysal hydrogeologic unit). The test is designed to determine the thermal-hydrologic responses of the unit to heating.
Site Characterization Plan	The plan that contains the strategy for completing a detailed set of activities that was expected to provide all of the information needed to comprehensively describe the repository system. The plan also documented methods for assessing the performance of the total repository system and its individual components. This was published by the U.S. Department of Energy in 1988 with subsequent updating ongoing.
Site Recommendation	A recommendation by the Secretary of Energy to the President that the Yucca Mountain site be approved for development as the nation's first high-level radioactive waste repository. If the site is determined to be suitable, this recommendation is expected in fiscal year 2001.
Smeared Heat Source	An attribute of mountain-scale thermal hydrology models in which the model handles heat output for waste packages by using the total heat produced by all assemblies in all waste packages, arrives at the entire repository-wide thermal load, and averages the thermal load across the entire repository heat area (~740 acres).
Sorb	To undergo a process of sorption.

Sorption	The binding, on a microscopic scale, of one substance to another. A term which includes both adsorption and absorption. The sorption of dissolved radionuclides onto aquifer solids or waste package materials by means of close-range chemical or physical forces is an important process modeled in this study. Sorption is a function of the chemistry of the radioisotopes, the fluid in which they are carried, and the mineral material they encounter along the flow path.
Sorption Coefficient (K_d)	Coefficient for a term for the various processes by which one substance binds to another.
Source Term	Types and amounts of radionuclides that are the source of a potential release from the repository.
Spalling	Flaking off of corrosion products from the metal substrate as it undergoes corrosion. The layer of corroded material thickens. The spalling could be caused by an expansive action of the corrosion products because they occupy a greater volume than the uncorroded metal substrate.
Spatial Variability	A measure of how a property, such as rock permeability, varies in an object such as a rock formation.
Speciation	The existence of the elements, such as radionuclides, in different molecular forms in the aqueous phase.
Spent Nuclear Fuel	Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing. Spent fuel that has been burned (irradiated) in a reactor to the extent that it no longer makes an efficient contribution to a nuclear chain reaction. This fuel is more radioactive than it was before irradiation, and it is hot. See also Burnup.
Steady-State Modeling	Modeling a system under the assumption that the variables are not changing with time. For example, flow fields can be simulated at a steady state if the boundary conditions, saturations, and fluxes are not changing with time.
Stream Tube	A modeling method used to represent the groundwater flow path from the water table to the biosphere. There are six stream tubes used for saturated zone modeling with one tube associated with and having the cross-sectional shape of, one of six regions designated at the water table. Each stream tube takes in groundwater flux and radionuclide mass flux data at the water table representing flux from the repository that has gone through the unsaturated zone.

Stochastic	Involving a variable (e.g., temperature and porosity) that may take on values of a specified set with a certain probability. Data from a stochastic process is an ordered set of observations, each of which is one item from a probability distribution. Random.
Stochastic Model	A model whose outputs are predictable only in a statistical sense. A given set of model inputs produces outputs that are not the same, but follow statistical patterns.
Stratigraphy	The branch of geology that deals with the definition and interpretation of the rock strata, the conditions of their formation, character, arrangement, sequence, age, distribution, and especially their correlation by the use of fossils and other means of identification.
Stress Corrosion Cracking	A cracking process that requires the simultaneous action of a corrosion mechanism and sustained tensile stress.
Structural Failure	Loss of waste package integrity to contain radionuclides.
Structure	In geology, the arrangement of the parts of the geologic feature or area of interest such as folds or faults. Structural features develop as a result of stresses that cause movements of the earth's crust and result in events such as earthquakes as the crust deforms.
Superpluvial Climate	One of three sets of conditions used to represent climate changes through time. Representative of wetter-than-normal climate conditions at Yucca Mountain, with precipitation three times that of the present-day climate. See also Dry Climate and Long-Term-Average Climate.
Surface Complexation	The process that describes the formation of complex molecules between the solute in the aqueous phase and the reactive groups on the solid surface, under specific chemical conditions.
Surrogate	Using one thing in place of another. An example is using a single important parameter, radionuclide travel time, as a surrogate for performance when the actual performance measure takes into account the effects of many factors. If the calculated travel time of radionuclides of interest is fast, that implies that performance of the natural and engineered barriers in containing the radionuclides is not as effective as it would be if radionuclide travel time was slow.
Tectonic	Pertaining to geologic forms or effects created by deformation of the earth's crust.
Tectonism	A general term for all movement of the earth's crust produced by tectonic processes.
Temperature Gradient	The rate of change of temperature with distance. When applied to the earth, the term geothermal gradient may be used.

Thermal-Chemical	Relating to thermal chemistry, the chemistry branch that studies heat changes that accompany chemical reactions and changes of state.
Thermal Conduction	The flow of thermal energy through a material. This conduction is affected by the amount of heat energy present, the nature of the heat carrier in the material, and the amount of dissipation.
Thermal-Hydrologic	Of or pertaining to changes in groundwater movement due to the effects of changes in temperature.
Thermal-Hydrologic Processes	Processes that are driven by a combination of thermal and hydrologic factors. These processes include evaporation of water near the repository when it is hot and subsequent redistribution of fluids by convection, condensation, and drainage.
Thermal Hydrology	The study of a system that has both thermal and hydrologic processes. A thermal-hydrologic condition, or system, is expected to occur if heat-generating waste packages are placed in the repository at Yucca Mountain.
Thermal Loading	The application of heat to a system, usually measured in terms of watt density. The thermal loading for a repository is the watts per acre produced by the radioactive waste in the active disposal area. The spatial density at which waste packages are emplaced within the repository as characterized by the areal power density and the areal mass loading.
Thermal Period	The time period in which thermal effects, such as higher temperatures or dried rock, are present in the region surrounding the repository.
Thermal Power Per Waste Package	The rate of heat released in watts by a particular waste package type. This will vary with fuel type and age, waste package capacity, and disposal configurations within waste packages.
Thermodynamic	Pertaining to the mechanical action of heat.
Thermodynamic/Kinetic Coefficients	Numbers that represent the rate of heat flow through a porous medium. An example is a coefficient that represents the rate of heat flow in a given type of rock.
Three-Dimensional Model	A three-dimensional representation of physical conditions and/or processes.
Time History	The predicted response of a system, expressed as a function of simulation time.
TOSPAC Computer Code	A computer code that simulates one-dimensional groundwater flow with the transport of decaying contaminants in partially saturated, fractured media.

Total Effective Dose Equivalent	The sum of the deep-dose equivalent, for external exposures, and the committed effective dose equivalent, for internal exposures.
Total System Performance Assessment (TSPA)	A risk assessment that quantitatively estimates how the proposed Yucca Mountain repository system will perform in the future under the influence of specific features, events, and processes, incorporating uncertainty in the models and data. Its purposes follow: (1) provide the basis for predicting system behavior and testing that behavior against safety measures in the form of regulatory standards (2) provide the results of TSPA analyses and sensitivity studies (3) provide guidance to site characterization and repository design activities (4) help prioritize testing and selection of the most effective design options.
TOUGH2 Computer Code	A computer program that simulates three-dimensional flow of groundwater and heat in unsaturated and saturated porous and fractured media. The code name is derived from Transport of Unsaturated Groundwater and Heat.
Toxicity	The ability of a substance to cause damage to cells or tissues of living organisms when the substance is inhaled, ingested, or absorbed by the skin. Acute toxicity is that which occurs over a short term of exposure, and chronic toxicity is that which occurs over a long term of exposure.
Tracer Testing	A procedure in which a soluble substance (tracer) is added to groundwater at one location, and its movement to another location is observed. Tracer testing is a technique by which groundwater flow directions and velocities and other hydrologic properties of rocks can be estimated.
Transient	Describing a variable that is changing with time. This occurs before development of a steady state condition.
Transient Modeling	Modeling of a system in which the variables are changing through time. Heating of the repository by the waste is a transient condition for which transient modeling is done.
Transparency	According to the Nuclear Waste Technical Review Board, the ease of understanding the process by which a study was carried out, which assumptions are driving the results, how they were arrived at, and the rigor of the analyses leading to the results. According to a Peer Review Panel report, transparency "requires ensuring completeness and using a logical structure that facilitates in-depth review of the relevant issues...achieved when a reader or reviewer has a clear picture of what was done in the analysis, what the outcome was, and why."

Transpiration	The process in which water enters a plant through its root system, passes through its vascular system, and is released into the atmosphere through openings in its outer covering. It is an important process for removal of water that has infiltrated below the zone where it could be removed by evaporation.
Transport	A process in which substances carried in groundwater move through the subsurface by means of the physical mechanisms of convection, diffusion, and dispersion and the chemical mechanisms of sorption, leaching, precipitation, dissolution, and complexation. Types of transport include advective, diffusive, and colloidal transport.
Transverse Dispersion	Dispersion of a solute moving in groundwater in directions transverse to the direction of the groundwater flow path. This movement may also be called lateral dispersion.
Tritium	A radioactive isotope of hydrogen that can be taken into the body easily, because it is chemically identical to natural hydrogen. Tritium decays by beta emission with a half-life of about 12.5 years.
TSPA Peer Review Panel	See Peer Review Panel.
Tuff	Igneous rock formed from compacted volcanic fragments from pyroclastic (explosively ejected) flows with particles generally smaller than 4 mm (0.16 in.) in diameter. The most abundant type of rock at the Yucca Mountain site.
Tuffaceous	A general term referring to any rock containing tuff.
Two-Dimensional Model	A two-dimensional slice through an entity, such as the earth's crust, usually in the horizontal and vertical directions, on which known features are placed and are used to predict likely features that may exist between points of known data. Mathematically, a model that represents physical conditions and/or processes; this mathematical model is composed of both horizontal rows and vertical columns of grid cells arrayed in L-shaped configurations only one grid cell thick. Also called a cross section.
Uncertainty	A measure of how much a calculated or estimated value that is used as a reasonable guess or prediction may vary from the unknown true value.
Undisturbed Performance	Refers to the expected or nominal behavior of the system as perturbed only by the presence of the repository. This is as used in description of scenarios, or features, events, or processes making up scenarios.

Unsaturated Zone	The zone of soil or rock below the ground surface and above the water table in which the pore spaces contain water, air, and other gases. Generally, the water saturation is below 100 percent in this zone, although areally limited perched water bodies (having 100 percent water saturation) may exist in the unsaturated zone. Also called the vadose zone.
Unsaturated Zone Flow	The flow of water in the unsaturated zone by downward percolation and by capillary action.
Unsaturated Zone Radionuclide Transport Model	A computer software code that defines the movement of radionuclides from the edge of the engineered barrier system, through the unsaturated zone, and to the boundary of the saturated zone.
Vadose Zone	See Unsaturated Zone.
Variable	See Section A.2 of this glossary.
Variability (Statistical)	A measure of how a quantity varies over time or space.
Velocity Field	The velocities of fluid flow, gas or liquid, in a region, which are generally depicted by arrows to indicate the direction and magnitude of the velocity.
Vitrified	Pertaining to a type of processed high-level radioactive waste where the waste is mixed with glass-forming chemicals and put through a melting process. The melted mixture is then put into a canister where it becomes a dry "log" of waste in a glassy matrix.
Vitrified Defense High-Level Radioactive Waste	A type of processed defense high-level radioactive waste that has been contained in a glass matrix.
Volcanism	Pertaining to volcanic activity.
WAPDEG Computer Code	A computer software code that was developed to model long-term corrosion degradation of waste disposal containers in the repository.

Waste Containment and Isolation Strategy	A document designed to assist the project management in prioritizing testing and analysis activities to focus on the most important issues in postclosure safety. It is also designed to help resolve uncertainty in processes and parameters of greatest significance to long-term performance. The document is still evolving. The key elements include the following: (1) Low groundwater flow amounts through storage area (2) Long-lived waste packaging (3) Cladding on the waste and low water content in waste to slow degradation (4) Engineered systems that promote slow dispersion/migration of radionuclides (5) Natural systems that promote slow dispersion/migration of radionuclides
Waste Form	A generic term that refers to radioactive materials and any encapsulating or stabilizing matrix.
Waste Package	The waste form and any containers (i.e., disposal container barriers and other canisters), spacing structures or baskets, shielding integral to the container, packing contained within the container, and other absorbent materials immediately surrounding an individual waste container placed internally to the container or attached to the outer surface of the disposal container. The waste package begins its existence when the outer lid welds are complete and accepted.
Waste Package Design Organization	The management and oversight department responsible for the waste package design and testing.
Waste Stream	Input of waste into the repository over time.
Water Flux	See Flux.
Water Table	The upper surface of a zone of saturation above which the majority of pore spaces and fracture openings are less than 100 percent saturated with water most of the time (unsaturated zone), and below which the opposite is true (saturated zone).
Weeps Model	A stochastic conceptual model of groundwater flow through fractured rock. The flow is assumed to occur through stochastically generated fracture paths, or weeps, with no interaction occurring between fracture and matrix.
Welded	Fused.
Welded Tuff	A tuff that was deposited under conditions where the particles making up the rock were heated sufficiently to cohere. In contrast to nonwelded tuff, welded tuff is considered to be denser, less porous, and more likely to be fractured (which increases permeability).

Young Spent Fuel, Old Spent Fuel	Terms used to designate groups of commercial spent nuclear fuels by their age since discharge from the power reactor. The young spent nuclear fuels are characterized by higher radiation levels and resulting higher heat outputs than the old spent nuclear fuels.
Yucca Mountain Waste Containment and Isolation Strategy	See Waste Containment and Isolation Strategy.
Zeolites	A large group of hydrous aluminosilicate minerals that act as molecular "sieves" because they can adsorb molecules with which they interact. At Yucca Mountain, they are secondary alteration products in tuff rocks when the rocks are exposed to groundwater and could act to retard the migration of radionuclides by their sieving action.
Zircaloy	An alloy material that may have any of several compositions including zirconium oxide. It is used as a cladding material.

A.2 GLOSSARY OF STATISTICS TERMS

Terms in this section are presented separately from the general glossary in Section A.1 because many of the statistical terms are defined in relation to other statistical terms. The terms are numbered to allow reference from the general glossary in Section A.1.

Coefficient of Multiple Determination	A measure of goodness of fit of a linear-regression model; a value near 1 indicates a good fit, meaning that the model is accounting for most of the uncertainty in the performance measure being analyzed.
Complementary Cumulative Distribution Function	A method of depicting the probability that a performance measure, such as dose, exceeds a given value. For most measures, the higher the value, the lower the probability.
Confidence	In statistics, a measure of how close the estimated value of a random variable is to its true value.
Confidence Interval	An interval that is believed, with a preassigned degree of confidence, to include the particular value of the random variable that is estimated.
Continuous Random Variable	Those variables whose value is determined by taking measurements and that can take <u>any</u> value of an infinite number of possible values within a certain value range. The concentration of radionuclides in water is a continuous random variable and, although ranging from zero to a value limited by the solubility of an individual radionuclide under given conditions, possible outcomes of dissolving a given radionuclide in water cannot be represented by a finite number of discrete values. This type of variable has a probability density function.

Correlation Coefficient	A coefficient (designated r) calculated in the analysis of paired data when neither of the variables can be singled out as of prior importance to the other and the study seeks to analyze their interdependence, as opposed to the dependence of one upon the other. This term is a dimensionless quantity that can be used (with certain reservations) as an absolute measure of the relationship between two variables. Mathematically, for two random variables, the ratio of their covariance to the product of their standard deviations. The correlation coefficient is also a measure of how close a scatter plot of points produced by one variable plotted against the other comes to falling on a straight line drawn through the trend of the points. In a negative correlation between the two variables, larger values of one are associated with smaller values of the other. In a positive correlation, larger values of one variable are associated with larger values of the other.
Covariance	For a pair of random variables, the expected value of the product of the deviations from their respective means. It measures the extent to which two variables vary together and if the variables are independent the covariance is zero (so is the correlation coefficient). If large values of one variable are associated with large values of the other, the covariance is positive, while if small values of one are associated with large values of another, the covariance is negative. The covariance is usually calculated to find the correlation coefficient.
Cumulative Distribution	For grouped data, a distribution that shows how many of the values are less than or more than specified values. For random variables this term is synonymous with distribution function.
Cumulative Distribution Function	For a continuous random variable, a function that quantifies the probability that the variable is no greater than any specified value of interest. The derivative of the cumulative distribution function is the probability density function. The cumulative distribution function is most commonly used to analyze continuous variables when data are not divided into categories (grouping by some qualitative description), and the probability density function is more appropriate when categorical studies of continuous random variables are performed.
Cumulative Probability	The probability that a random variable will have a value equal to or less than some specified value.
Dependent Variable	A variable whose value depends on one or more other variables. For example, the value (amount) of body weight is a variable that depends on several independent variables—the amount of calories taken in and the amount of calories burned, as well as genetics and probably other factors. As another example, the thermal load per acre of the repository is a dependent variable—it depends on the type, number, and spacing of waste packages emplaced.

Discrete Random Variables	Those variables whose values are finite, or countable in numbers. The number of waste packages of each type is a discrete variable. Discrete random variables have associated with them probability functions that tell the probability that the variable takes on any particular value. For example, in throws of two unbiased dice, the probability that the value of the numbers shown on the dice (a discrete random variable) for any throw will be two is one in 36; the probability function is 1/36.
Distribution	The overall scatter of values for a set of observed data. A term used synonymously with frequency distribution. Distributions have probability structures that are the probability that a given value occurs in the set.
Distribution Frequency	A representation of how values of an outcome or variable are distributed over the range of expected values.
Distribution Function	A function whose values are the probabilities that a random variable assumes a value less than or equal to a specified value. Synonymous with cumulative distribution.
Expected Value	A variable's mean, or average, outcome. The weighted average of the number of possible outcomes, with each outcome being weighted by its probability of occurrence. The mean of a probability distribution of a random variable that one would expect to find in a very large, random sample. The sum of the possible values, each weighted by its probability—the center of the random variable's histogram (frequency distribution).
Frequency Distribution	Formed when data are grouped into classes (or ranges of values within the overall set of values, such as 1 to 5, 5 to 10, 10 to 20, etc.), with the classes listed in a table (or other format) showing the number of data points that occur in each class.
Function (Mathematics)	A quantity that is variable and whose value depends on and varies with the value of another quantity or quantities. Functions show the mathematical relationship between dependent variables and the independent variables upon which the value of the dependent variables depend.
Histogram	A bar graph representation of a frequency distribution having frequency of occurrence as the ordinate (y axis) and classes of values observed in sampling of the variable as the abscissa (x axis). The area of each rectangle in the histogram represents the proportion of observations (relative frequency) that fall in that interval. This is the relative frequency of observations that lie between the two values that form the class boundary. It is not for a single value but is relative frequency of the class interval.
Linear Correlation	The relationship between two or more random variables for which the regression equations are linear.

Linear Regression	A regression where the relationship between the (conditional) mean of a random variable and one or more independent variables can be expressed by the mathematical equation that describes a line. A relationship between two variables such that the dependence of one variable on the other can be described by (the equation of) a straight line.
Linear Stepwise Regression	An analysis designed to determine variables that have the greatest influence on an output value (e.g., peak dose rate) when there are many variables whose input values go into the calculation. In simple terms, a linear regression is performed for a line in a multidimensional space, and the correlation of the values of different variables to the line are examined by performing the calculation multiple times and varying the value of one variable at a time while holding the others constant. This is a stepwise process in which one variable at a time is examined to determine the impact of its influence on the final outcome (peak dose rate, for instance).
Mean (Arithmetic)	For a statistical data set, the sum of the values divided by the number of items in the set. The arithmetic average.
Mode	A measure of location in a data set defined as the value which occurs with the highest frequency. For qualitative data it is the attribute which occurs most frequently. A set of data or a distribution can have more than one mode, or if no two values are alike, no mode. For the distribution of a random variable the mode is the value for which the probability function or probability density is at the relative maximum.
Monte Carlo (Uncertainty) Analysis	An analytical method that uses random sampling of parameter values available for input into numerical models as a means of approximating the uncertainty in the process being modeled. A Monte Carlo simulation comprises many individual runs of the complete calculation using different values for the parameters of interest as sampled from a probability distribution. A different final outcome for each individual calculation and each individual run of the calculation is called a realization. Each realization is equally likely to occur in the Monte Carlo process.
Percentile	For a large data set where specific values are not repeated extensively, used to indicate where a value lies in relation to the entire group of values. For example, the 25th percentile indicates that about 25 percent of the items are smaller than this value and about 75 percent are larger than this value.
Probability	The relative frequency with which an event occurs in the long run. Statistical probability is about what really happens in the real world and can be verified by observation or sampling. Knowing the exact probability of an event is usually limited by the inability to know, or compile the complete set of, all possible outcomes over time or space.

Probability-Density Function	A frequency distribution such that the bars of a histogram that would represent it are so narrow that their tops would form a smooth curve if connected by a line. The curve is the probability density function. This type of distribution can be made if the number of observations of the value of a continuous random variable increases indefinitely, and the width of the range represented by each class (class interval) becomes smaller and smaller. The area under the density function curve between any two points on the curve, such as x_1 and x_2, represents the probability that the value of the random variable will lie between these two values.
Probability Distribution	The set of outcomes (values) and their corresponding probabilities for a random variable.
Quantile	A value at or below which lies a given fraction (1/5, 30 percent, etc.) of a set of data. Also called fractile.
R^2	A correlation coefficient that quantifies the goodness of fit of a linear regression model to an output value such as peak dose rate. A value of one corresponds to a perfect fit.
R^2 - Loss	The amount of change in fit when a variable is dropped from a linear stepwise regression analysis. For example, look at a linear stepwise regression analysis such that the out put (e.g., dose) is calculated using 10 variables and the total R^2 is 0.80 (1 corresponds to a perfect fit). If the analysis is then performed with one of the variables left out and the R^2 is 0.78 (meaning it changed or lost very little), then that variable does not contribute strongly to the fit. If the loss is large such as going from 0.80 to 0.60, then the variable does contribute strongly to the fit. This is a method of showing to which variables the outcome (peak dose) is most sensitive or responsive.
Random Variable	A property that has a numerical description and is determined by the outcome of a random experiment or random sampling. The different values of the random variable have different probabilities of occurrence. Also called variates.
Range (Statistics)	The numerical difference between the highest and lowest value in any series.
Rank Transformation	A type of data transformation used either to reduce the influence of extreme values or to deal with non-linearities in data sets. Data will fit better to a non-linear curve if it is first put into ranks. In ranking, the data values of both input and input data are replaced with the rank of that data value within the data set. The smallest value of a data set is replaced with the number 1, the second smallest is replaced with the number 2, and so forth up to the largest value in the set.

Regression	The relationship between the (conditional) mean of a random variable and one or more independent variables.
Regression Analysis	The analysis of paired data such that one member of the pair is a constant and the other is a random variable. The analysis of a paired dependent variable and the independent variable upon which it depends. For example, the term was first used in a study of the heights of fathers and sons where a regression (or turning back) was observed toward the mean height of the population in the heights of sons whose fathers were taller or shorter than the mean.
Scatter Plot	(1) A set of points arrived at by plotting paired values as points in a plane. (2) A two-dimensional dot plot.
Standard Deviation	(1) For a set of observations or a frequency distribution, the square root of the average of the squared deviations from the mean divided by n-1 (where n is the sample size). (2) The square root of the variance.
Variable	A nonunique property or attribute.
Variance	(1) The square of the standard deviation. (2) The expected squared distance from the population mean of a random variable, sometimes called the population variance.

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