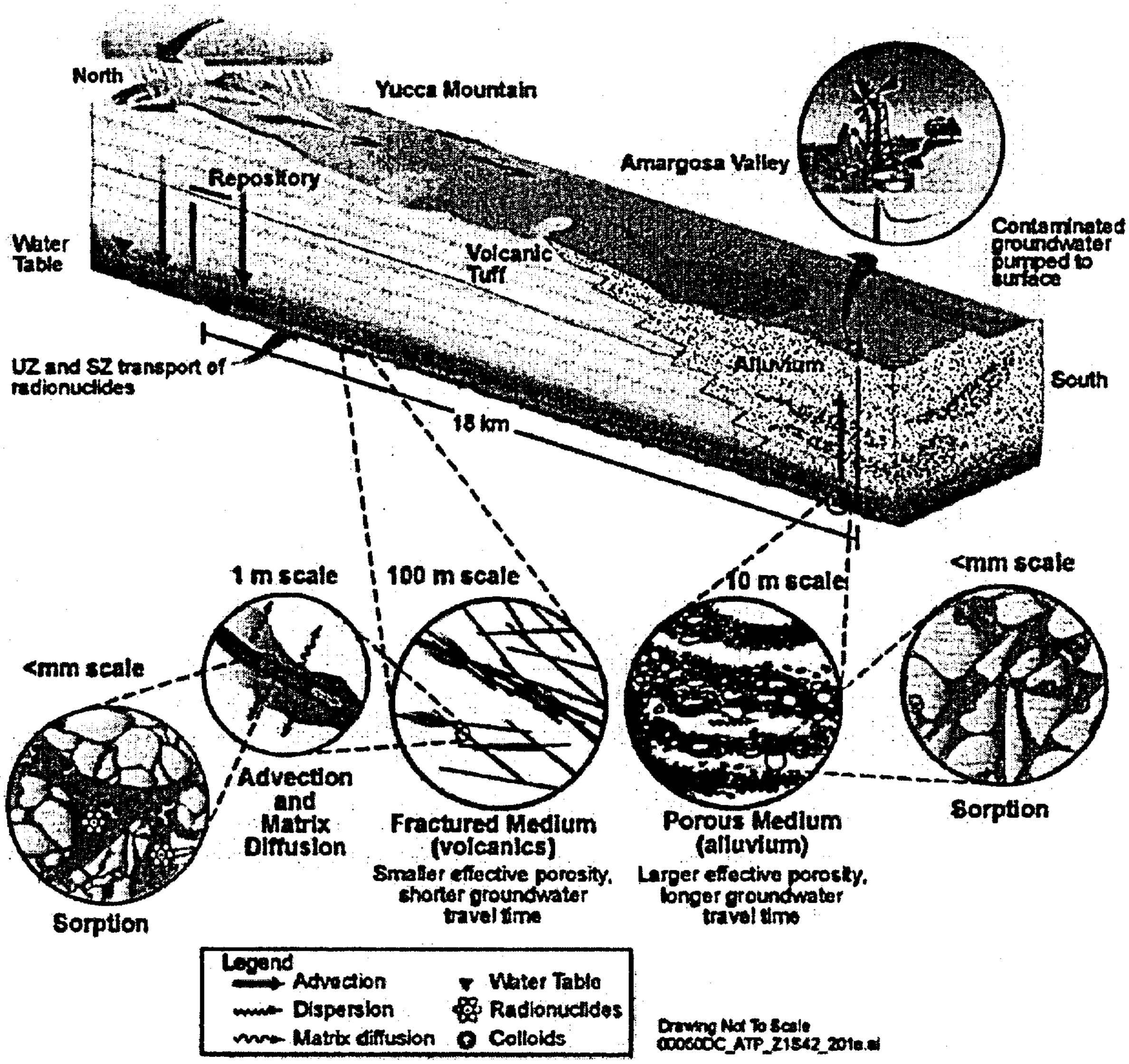


Figure 4-128. Conceptualization of Features and Processes Important to Saturated Zone Transport
This schematic illustration presents transport processes in fractured and porous media flow at Yucca Mountain, providing a conceptualization of transport through the saturated zone to the location of the reasonably maximally exposed individual in the Amargosa Valley. Moving groundwater carries (advects) dissolved or suspended radionuclides in fractures in the volcanic rocks and in pores between individual rock grains in the alluvium. The processes of diffusion and sorption slow the transport of radionuclides to the accessible environment. Radionuclides diffuse into and out of the unfractured portion (matrix) of the volcanic rocks. In the alluvium, radionuclides diffuse into and out of regions where water is stagnant or flows very slowly. UZ = unsaturated zone; SZ = saturated zone.

and Transport Process Model Report (CRWMS M&O 2000bn).

4.2.9.1 Conceptual Basis of Flow and Transport

The following discussion of the conceptual basis for the site-scale saturated zone flow and transport model is a summary of information presented in Section 3.2 of *Saturated Zone Flow and Transport Process Model Report* (CRWMS M&O 2000bn).

Flowing groundwater transports radionuclides either in solution (dissolved) or in suspension, bound to very small particles known as colloids. Colloid particles are small enough to travel with flowing water through fractures in volcanic rocks, pores in the unfractured portion (matrix) of volcanic rocks, and pores in alluvium. Radionuclide releases from water contacting breached waste packages in the potential repository would have to migrate a distance ranging from approximately 210 m (690 ft) to 390 m (1,300 ft) downward to the water table, then migrate downgradient in the saturated zone to reach the accessible environment. The average distance of the potential repository above the elevation of the water table is about 300 m (1,000 ft). Groundwater in the saturated zone generally moves southeast from beneath the potential repository before flowing south out of the volcanic rocks and into the thick valley fill deposits of the Amargosa Desert.

The water table under most of the potential repository is in the Tertiary age Crater Flat Group. This stratigraphic unit is also referred to by a hydrostratigraphic name, the lower volcanic aquifer. It is composed of three tuffs: the Tram, Bullfrog, and Prow Pass. After reaching the water table, flow continues away from the immediate vicinity of the potential repository site in the Crater Flat Group. Permeability of tuffs in the Crater Flat Group is small where the rocks are not fractured. Consequently, most flow of groundwater in these rocks occurs in fractures.

The volcanic rocks are about 2,000 m (6,500 ft) thick at the site, but they gradually thin to 0 m (0 ft) with increasing distance from the site. At a distance of 10 to 20 km (6 to 12 mi) along the travel path from the potential repository, groundwater flow enters alluvium and remains in alluvium to the accessible environment. Flow in alluvium is modeled as movement through pores between rock grains rather than in fractures.

The quantity of groundwater that flows through a unit area of rock per unit period of time is known as the specific discharge. To maintain the same specific discharge in volcanic rocks and alluvium, the velocity of flow must be slower in the alluvium because the effective porosity of the alluvium is larger than the fracture porosity of the volcanic rocks. Results of the saturated zone site-scale flow model show that specific discharge does not change greatly along flow paths from the repository to the receptor location. Consequently, flow velocities are faster in volcanic rocks than in alluvium. Figure 4-129 shows possible flow paths from the potential repository, as well as the portions of the flow paths in tuff and alluvium. The portion of the flow paths in tuff is shown in red, and the portion in alluvium is blue. The location of the contact of tuff and alluvium is uncertain and is treated stochastically in TSPA-SR calculations. This figure shows the contact to be at the expected-value location.

The flow paths described previously are inferred from a site-scale flow model. This model results in a flow field that is consistent with available information concerning geology, rock hydraulic properties, groundwater chemistry, and measured water levels. One feature of the simulated three-dimensional flow field is higher hydraulic head in carbonate rocks at depth than in the rocks containing the simulated flow paths from below the potential repository. The carbonate rocks are relatively permeable and laterally continuous. They are sometimes referred to by the hydrostratigraphic name, the regional carbonate aquifer. The upward gradient of hydraulic head from the carbonate rocks to the overlying tuffs is observed in boreholes located within the more extensive Death Valley Regional Flow System and is supported by regional-scale flow modeling (D'Agnese, Faunt et al. 1997). In addition, the upward gradient is observed in the only borehole in the vicinity of Yucca Mountain to penetrate the regional carbonate aquifer. This potential for upward flow is

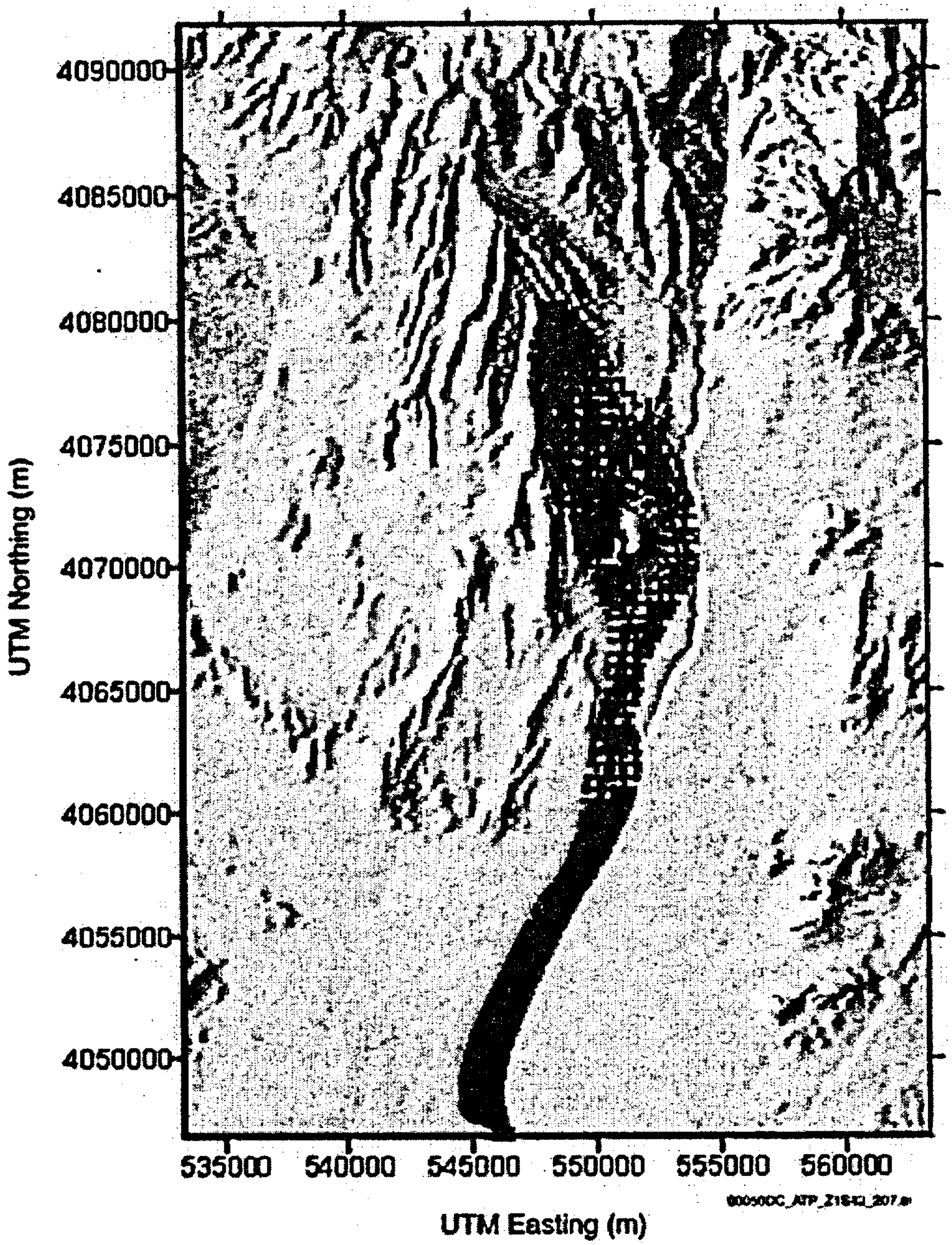


Figure 4-129. Flow Paths Predicted by the Site-Scale Saturated Zone Flow and Transport Model for the TSPA-SR

The repository is located in the upper central part of the figure. The released particles move from the upper central area in the figure to the bottom. The red portion of the illustrated particle positions corresponds to an area of flow through fractured volcanic tuff while the blue part of the flow path is through alluvium, modeled as a porous medium. The spatial pattern in the volcanic tuff reflects the numerical algorithm that illustrates particle positions at grid boundaries or at the end of a time step. The location of the contact of tuff and alluvium is uncertain and is treated stochastically in TSPA-SR calculations. This figure shows the contact to be at the expected-value location. Source: Adapted from CRWMS M&O 2000a, Figure 3.8-21.

significant for the performance of the potential repository because it prevents downward flow of contaminants from Yucca Mountain into the regional carbonate aquifer.

Several processes act to slow the movement of radionuclides or to dilute their concentration (Figure 4-128). The processes that slow, or retard, the movement of radionuclides are important in that longer travel times allow more time for radioactive decay to occur. One important retardation process is sorption onto mineral surfaces. The sorption process is reversible. Consequently, a portion of the radionuclides at a particular location will be sorbed to rock surfaces, and a portion will be in solution in the groundwater. Multiple cycles of sorption and desorption slow the movement of radionuclides relative to the groundwater flow rate.

Diffusion of dissolved or colloidal radionuclides into regions of very slowly moving groundwater is a second important retardation process. Diffusion will occur from water flowing in the fractures of the volcanic rocks into the matrix, or nonfractured, portion of these rocks, as well as from water in pores between rock grains in the alluvium into porosity within the rock grains. In either case, the radionuclides will eventually diffuse back out into the moving groundwater. However, multiple cycles of diffusion into and out of the rock matrix and grains slows the rate of transport.

Finally, hydrodynamic dispersion, or spreading of solutes, along the flow path can decrease the concentration of radionuclides in groundwater (Figure 4-130). Dispersion is mainly due to differences in flow velocity at a microscopic scale or by larger-scale heterogeneity of permeability.

4.2.9.2 Summary State of Knowledge

In this section, data are presented that support selected aspects of the conceptual basis and modeling of radionuclide transport through the saturated zone. In addition, natural analogues for these processes are discussed.

The transport of radionuclides potentially released from a repository is closely tied to the behavior of water flowing through the host subsurface material because liquid water is the principal medium in which radionuclides are transported to the potential downgradient receptor (CRWMS M&O 2000bn, Section 3). If released, radionuclides would primarily move in groundwater as solute or attached to colloids. The transport of radionuclides as solute is affected by the three processes discussed in the previous section—advection, diffusion, and dispersion—and, for reactive constituents, by sorption. In addition, transport of radionuclides attached to colloids is affected by filtering, in which colloids with diameters greater than the pore openings are "sieved" by the medium. Transport of filtered particles is thereby retarded with respect to advective flow. Chemical precipitation, retardation (slowing the movement of radionuclides to less than the velocity of groundwater), and dilution (reducing the concentration) of radionuclides in the groundwater all affect the concentration of radionuclides released to the environment.

4.2.9.2.1 Advection

C-Wells Testing—Results from the hydraulic and tracer testing completed at the C-Wells Complex (Figure 4-131) were used to identify and confirm the conceptualization of flow and transport in the fractured tuff and to derive flow and transport parameters used in the modeling. Data from the testing are discussed in the next sections on advection, dispersion, matrix diffusion, and sorption. Ongoing testing at the Alluvial Testing Complex located at Nye County Well 19D, shown in Figure 4-131, will provide additional information on flow and transport in the alluvium.

Advection in the Fractured Porous Media—Hydrologic evidence supports the model of fluid flow within fractures in the moderately to densely welded tuffs of the saturated zone (CRWMS M&O 2000bn, Section 3.2.2). Bulk hydraulic conductivities measured in the field tend to be several orders of magnitude higher than hydraulic conductivities of intact tuff core samples measured in the laboratory. Also, there is a positive correlation between fractures identified using acoustic televiewer or borehole television tools and the zones of high transmissivity and flow (Erickson and Waddell 1985, Figure 3).

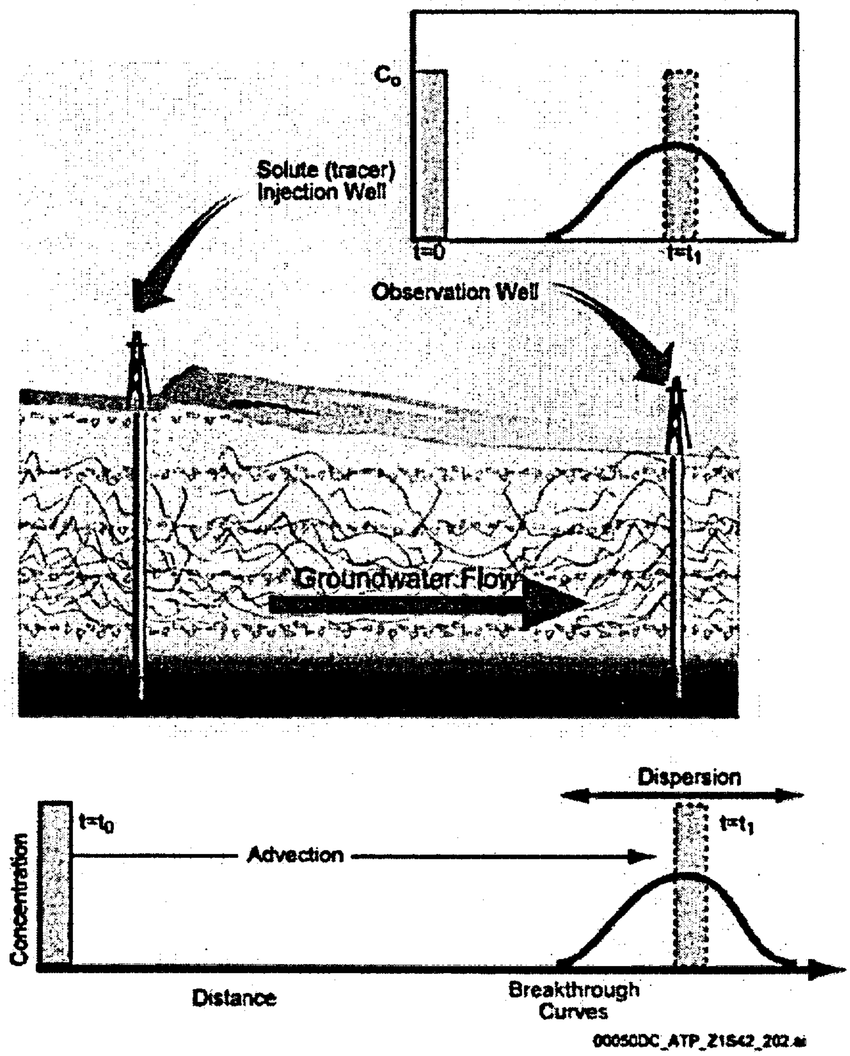


Figure 4-130. Concepts of Advection and Dispersion in Porous Medium and the Resulting Breakthrough Curves Defined by the Time History of Solute Concentration Measured in a Well
The initial volume at the well on the left illustrates the introduction of a solute plume at time t=0. As the solute moves downstream (by advection) to an observation well, it spreads by dispersion. The dotted volume illustrates the effect of advection only. The breakthrough curve gives the time-dependent concentration history at the observation well.

Fractures have important effects on the hydrology at Yucca Mountain, and the permeability distribution and principal flow directions depend strongly on the spatial distribution and orientations of fractures.

The laboratory work of Peters et al. (1984, Appendix E), in which fracture hydraulic apertures were found to be relatively insensitive to confining pressures, suggests that the spatial distribution of fractures (densities and interconnectivities) is more important in determining hydraulic conductivity as a function of direction than the effect of the stress field on the apertures of individual joints.

Numerical simulations (Brown 1987) suggest that there is a propensity of fluid and solutes to travel preferentially along channels in fractures where apertures are largest. Thus, for flow within fractures in the saturated zone, a fracture-flow model recognizing and accounting for flow channels may be necessary.

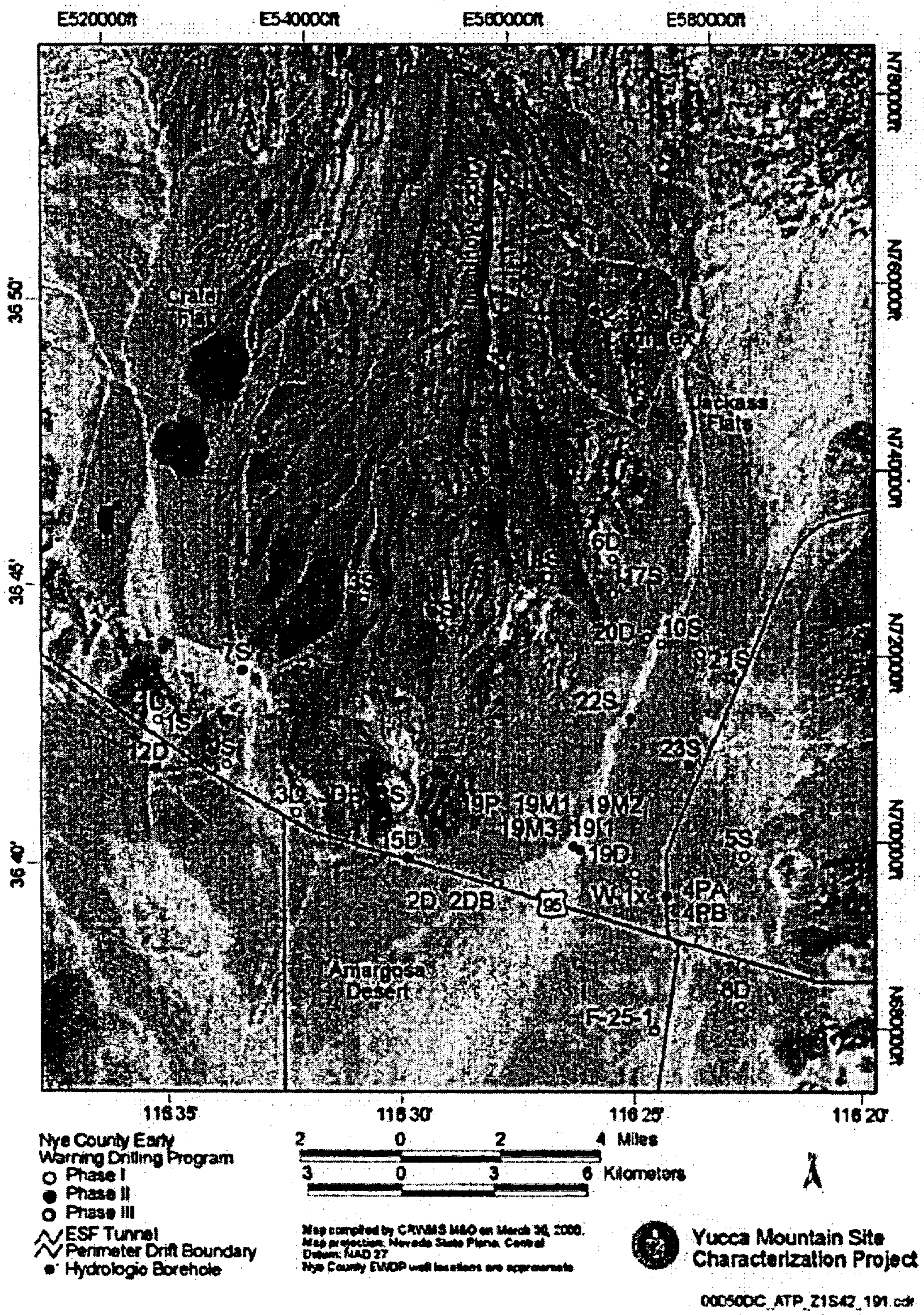


Figure 4-131. Nye County Early Warning Drilling Program Boreholes, the C-Wells Complex, and 19D (the Location of the Alluvial Testing Complex)
Source: CRWMS M&O 2000bn, Figure 2-3.

Fractures generally are found within the moderately to densely welded tuffs, so the range of matrix porosities of these tuffs (0.06 to 0.09 for densely welded and 0.11 to 0.28 for moderately welded) probably best reflects the matrix fluid storage capacity of interest for saturated zone transport calculations (CRWMS M&O 2000bn, Section 3.2.4.1.1).

Advection in the Alluvium—Due to the more porous and less fractured nature of the porous alluvial material, fluid flow in the alluvium is well represented using a porous continuum conceptual model. However, this assumption does not mean that the medium is homogeneous. On the contrary, flow is likely to occur through the more permeable regions within the medium, with the low-permeability regions acting as flow barriers that groundwater flows around rather than through. Ongoing Nye County Early Warning Drilling Program drilling and the Alluvial Testing Complex testing will provide more data to quantify the alluvium portion of the flow. Hydrologic parameters used in numerical models were selected to be conservatively bounding. Fluid flow is represented using a porous continuum with a constant and conservative permeability value. Transport parameters are assigned based on uncertainty distribution of the parameters.

Fracture Properties—Fracture properties (such as aperture, frequency, mineralogy, and saturation, as shown in Figure 4-132) affect fracture–matrix interactions, dispersion, sorption, and the transport of aqueous and colloidal species. The fracture apertures are derived from the fracture porosity and fracture–matrix connection area (CRWMS M&O 2000ed, Section 6.2.1). A log-normal distribution of apertures for all the model layers beneath the potential repository is sampled stochastically in the transport calculations for TSPA.

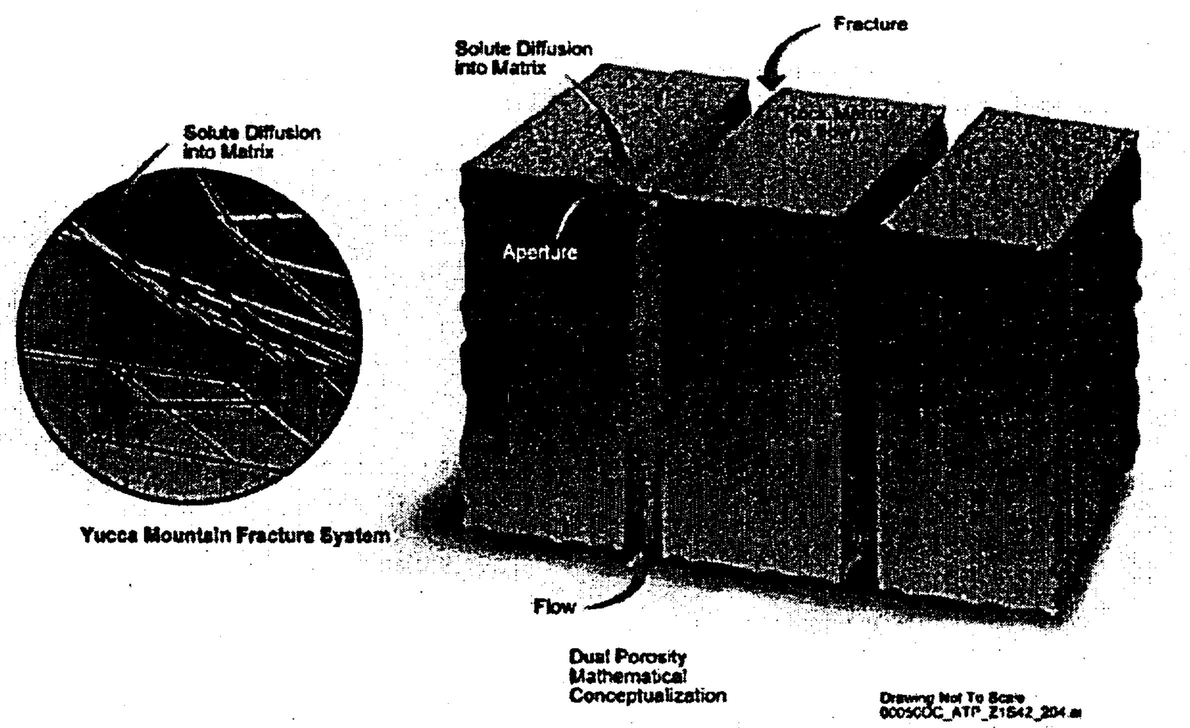


Figure 4-132. Fracture Properties of Aperture (Width), Length, and Frequency (Number of Fractures per Volume)

These parameters vary spatially in real geological media. The dual-porosity mathematical conceptualization assumes stagnant water in a porous rock matrix of high porosity and low permeability and relatively rapid flow in the fracture network of low porosity and high permeability. Solute enters and leaves the matrix rock through matrix diffusion.

In the saturated zone, the main distinction between the volcanic aquifers and the confining units is that the aquifers tend to be more welded and contain more permeable fractures. However, alteration of the tuffs to zeolites and clays, which reduces permeability, is more pronounced at depth, and the greater pressure at depth tends to reduce fracture permeability. Consequently, a combination of factors, including fracture properties, mineralogy, and depth, rather than just rock type, determines the hydrologic character of the volcanic rocks below the water table at Yucca Mountain.

Hydraulic tests have been performed to determine the properties of the saturated zone volcanic units. The analyses are limited by uncertainties about the extent to which fractures affect the unit conductivity (a measure of the ability of the subsurface material to transmit flow) (Luckey et al. 1996, pp. 32 to 36). However, the confining units had a low range of conductivities (0.000005 m to 0.26 m [0.00002 to 0.85 ft] per day), whereas the aquifers had a range of moderate to high conductivities (0.00004 m to 18 m [0.0001 to 59 ft] per day). Intervals without open fractures in all units tend to have low hydraulic conductivity, reflecting the conductivity of the rock matrix or of small fractures (Luckey et al. 1996, p. 32). Conversely, larger values of apparent hydraulic conductivity for both aquifers and confining units can generally be attributed to fractures.

Hydraulic tests at Yucca Mountain were performed in single-borehole and multiple-borehole tests (C-Wells Complex). Transmissivities, which are a measure of the ability of the entire thickness of the rock unit to transmit water, were measured in the multiwell tests and tend to be approximately 100 times greater than those determined from single-borehole tests in the same borehole. This observation suggests that the multiwell tests, which sample larger subsurface volumes, are also encountering a larger number of permeable fractures (Luckey et al. 1996, p. 36). The test results also support the hypothesis that fractures are more important than matrix in controlling hydraulic conductivity of the volcanic rocks in the saturated zone.

Groundwater Flow Paths—The concentrations of chemical constituents in groundwater that do not react with the subsurface material (i.e., conservative constituents) can be used to help delineate groundwater flow paths both on a regional and a local basis (CRWMS M&O 2000eg, Figure 5). Maps of areal variations in the concentrations of such constituents as chloride in the Yucca Mountain region delineate flow paths with generally north–south orientations (Figure 4-133). Flow paths from the potential repository first trend to the southeast towards Fortymile Wash and then, after reaching Fortymile Wash, trend more southerly. Whether water from the potential repository horizon mixes with water moving southward along Fortymile Wash is unclear. If such mixing does take place, it could substantially dilute the concentrations of any radionuclides that might be released from the potential repository. If not, radionuclides that might be released from the potential repository could be confined to the somewhat slower flow paths generating from below Yucca Mountain.

The time at which a given body of water is recharged can generally be bounded through an analysis of isotopic data for hydrogen, oxygen, carbon, and chlorine. Data on isotopic compositions of hydrogen and oxygen in saturated zone waters in the Yucca Mountain region suggest that the waters of southern Yucca Mountain and eastern Crater Flat infiltrated under cooler conditions than the waters of northern and eastern Yucca Mountain, which in turn were infiltrated under cooler conditions than waters along Fortymile Wash (CRWMS M&O 2000eg, Section 6.5.4.1). Through comparisons of the isotopic data for waters in modern climatic regimes, it is likely that the cooler conditions reflected in the waters of southern Yucca Mountain and eastern Crater Flat were associated with the end of the last ice age approximately 10,000 years ago. Carbon isotopic data (including carbon-14 measurements) for these waters are consistent with such a conclusion (CRWMS M&O 2000eg, Section 6.5.4.2.1). Unfortunately, the carbon isotopic data do not allow the derivation of more accurate groundwater ages because of uncertainty in the degree to which the original atmospheric carbon-14 signal in infiltrated waters may have been modified by dissolution of preexisting carbonate minerals. As a

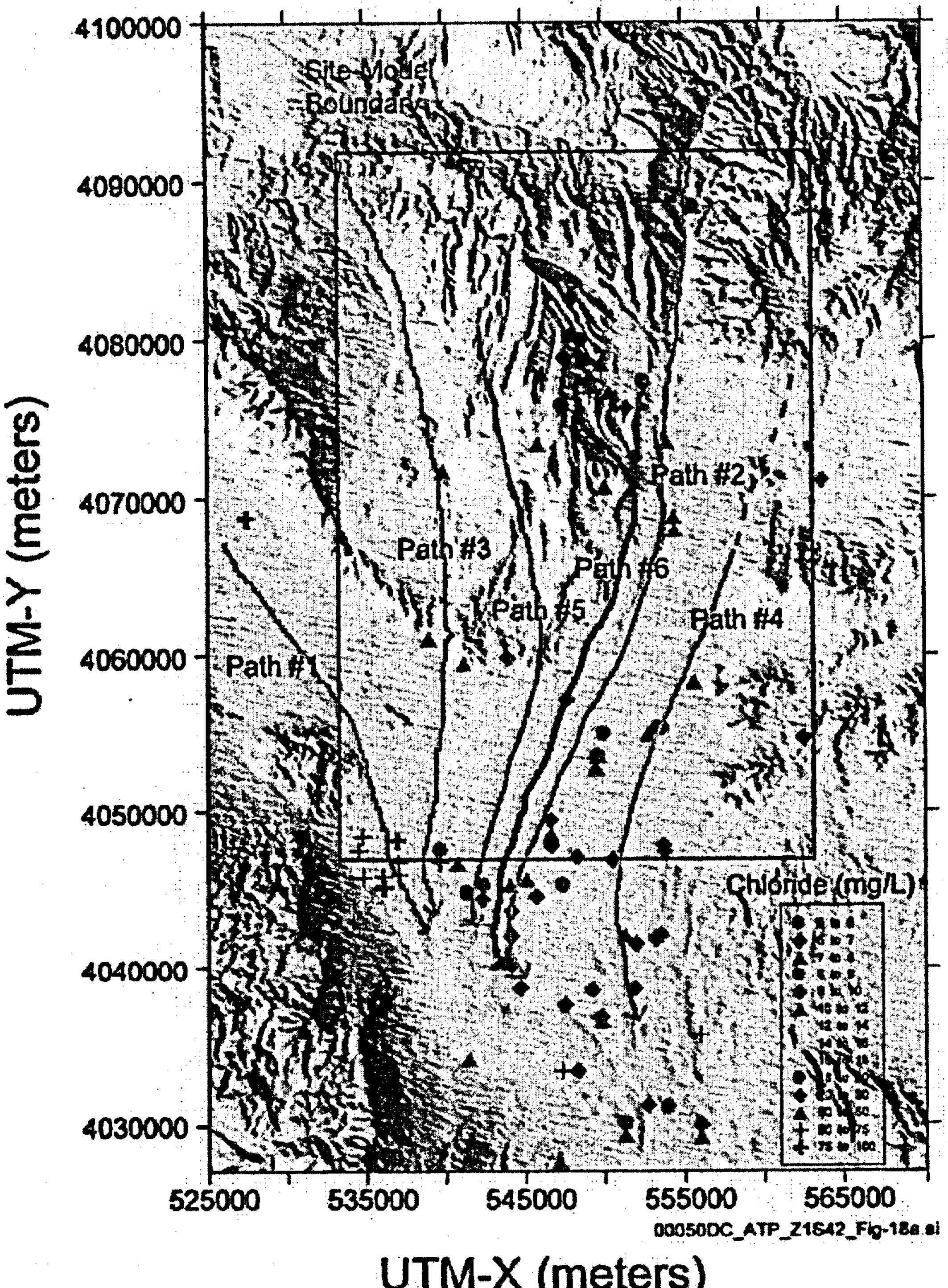


Figure 4-133. Groundwater Flow Paths near Yucca Mountain as Inferred from Chloride Concentrations at Sites near Yucca Mountain

The red arrow shows the groundwater flow path from Yucca Mountain. The blue arrows show other regional groundwater flow paths that constrain the Yucca Mountain flow path. UTM = Universal Transverse Mercator. Source: Modified from CRWMS M&O 2000bn, Figure 3-3.

consequence, groundwater ages calculated on the basis of observed carbon-14 values are maximum ages (CRWMS M&O 2000eg, Section 6.5.4.2.1).

The apparent age of groundwater in Fortymile Wash is younger than the age of groundwater beneath the potential repository (CRWMS M&O 2000eg, Section 6.5.4.2.1). This result implies that, if there is groundwater mixing, groundwater below the potential repository makes up at most a small fraction of the groundwater beneath Fortymile Wash. It also suggests the possibility that flow paths from the area of the potential repository may have a more southerly orientation than suggested by the chlorine data (Figure 4-133).

The expected flow path of groundwater moving away from the potential repository in the saturated zone passes into the valley-fill deposits approximately 15 km (9.3 mi) or more south of Yucca Mountain. Beginning in 1999, numerous boreholes have been drilled in the valley fill as part of the Nye County Early Warning Drilling Program (Figure 4-131). Additional holes are scheduled to be drilled in later phases. In addition to providing a monitoring system for Amargosa and Pahrump valleys, these holes are designed to provide information about the lithology, water levels, hydraulic properties, and transport properties of the valley fill. This information should enable the DOE to limit the uncertainties and conservatism in the current site-scale saturated zone flow and transport model.

4.2.9.2.2 Matrix Diffusion

Instead of simply traveling at the flow rate of the fluid in the saturated zone, radionuclides will potentially undergo physical and chemical interactions that must be characterized to predict large-scale transport behavior. In the laboratory, the effect of matrix diffusion has been clearly demonstrated by rock-beaker, diffusion-cell, and fractured-rock-column experiments (CRWMS M&O 2000eb, Section 6.6). Transport models incorporating matrix-diffusion concepts have been proposed to explain the inconsistencies between groundwater ages obtained from carbon-14 data and those predicted from flow data. In the field, interwell tracer tests that demonstrate the effect of matrix diffusion have been conducted (CRWMS M&O 2000eb, Section 6). These laboratory experiments and field tests have demonstrated the validity of matrix diffusion and provided a basis for quantifying the effect of matrix diffusion on radionuclide migration through the moderately and densely welded tuffs of the saturated zone at Yucca Mountain. Because the effect of matrix diffusion on transport through the saturated zone could be important, it is incorporated into the TSPA model of radionuclide migration.

When a dissolved species travels with the groundwater within a fracture, it may migrate by molecular diffusion into the relatively stagnant fluid in the rock matrix. When a molecule enters the matrix, its velocity effectively goes to zero until Brownian motion carries it back into a fracture. The result of moving into the stagnant matrix is a delay in the arrival of the solute at a downgradient location from that predicted if the solute had remained in the fracture.

As described in *Saturated Zone Transport Methodology and Transport Component Integration* (CRWMS M&O 2000eh), mathematical models were first used to demonstrate the likely effect of matrix diffusion and flow in fractured media. In these studies, transport was idealized as plug flow in the fracture with diffusion into the surrounding rock matrix. Experiments were performed on transport in natural fissures in granite, and it was concluded that matrix diffusion was necessary to model conservative tracer data. The concept of matrix diffusion was extended to examine the coupling between matrix diffusion and channel flow usually thought to occur within natural fractures.

Often, groundwater ages obtained from carbon-14 data are greater than those predicted from flow data. Sudicky and Frind (1981) developed a model of flow in an aquifer with diffusion into a surrounding aquitard and showed that the movement of carbon-14 can be much slower than that predicted assuming only movement with the flowing water. Maloszewski and Zuber (1985) reached a similar conclusion with a model for carbon-14 transport that consists of uniform flow through a network of equally spaced fractures with diffusion into the surrounding rock matrix. Their model also includes the effect of chemical-exchange reactions in the matrix, which further slows the migration velocity. They also present analyses of several interwell tracer experiments showing that the matrix-diffusion model can be used to provide simulations of these tests that are consistent with the values of matrix porosity obtained in the laboratory and aperture values estimated from hydraulic tests. In all cases, the results are superior to previous analyses that did not include the effects of matrix diffusion. Finally, of greatest relevance to the saturated zone beneath Yucca Mountain is the C-Wells reactive tracer test (CRWMS M&O 2000bn, Section 3.1.3.2), which demonstrated that models incorporating matrix diffusion provide more reasonable fits to the tracer-experiment data than those that assume a single continuum. Maloszewski and Zuber (1985) demonstrated that a suite of tracers with different transport characteristics (diffusion coefficient, sorption coefficient) produced breakthrough curves that can be explained with a model that assumes diffusion of tracers into stagnant or near-stagnant water in the matrix pores (Figure 4-134).

Data from naturally occurring isotopes such as carbon-14 provide valuable clues into the processes controlling transport in the saturated zone. The apparent ages of saturated zone fluids are several thousand years or more (CRWMS M&O 2000bn, Section 3.1.2.3). These ages imply

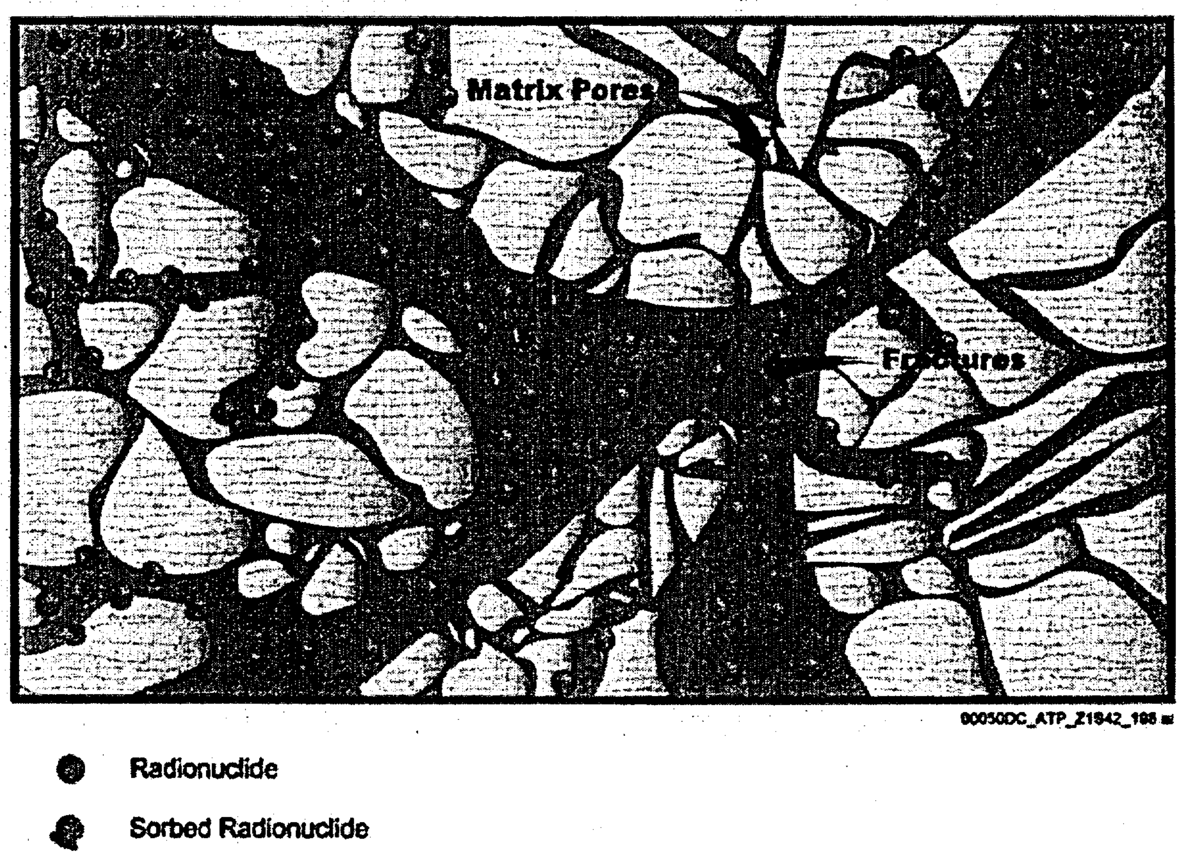


Figure 4-134. Conceptualization of Solute and Colloid Transport in a Fracture with Sorption in the Rock Matrix

Sorption in the fracture rock is conservatively ignored in TSPA-SR calculations. After diffusing into the matrix, solutes are sorbed into the rock matrix. Source: CRWMS M&O 2000a, Figure 3.7-4.

that either transport of carbon is slowed by matrix diffusion or advective porosity is much larger than expected for a fractured media. This argument is consistent with the conceptual model of interchange of solutes between the fractures and matrix found in the matrix-diffusion model (CRWMS M&O 2000bn, Section 3.2.4.2).

4.2.9.2.3 Hydrodynamic Dispersion

Dispersion is caused by heterogeneities from the scale of individual pore spaces to the thickness of individual strata and the length of structural features such as faults. The spreading and dilution of radionuclides that results for these heterogeneities could be important to performance of the potential repository. The largest heterogeneities are represented explicitly in the site-scale saturated zone flow and transport model (CRWMS M&O 2000bn, Section 3.2.4.4) in that these features are embodied in the hydrogeologic structure on which the model is built. For dispersion at smaller scales, dispersion is characterized using an anisotropic dispersion coefficient tensor consisting of a three-dimensional set of values: longitudinal, horizontal-transverse, and vertical-transverse dispersivities.

Transport field studies have been conducted at a variety of length scales from meters to kilometers to address the issue of dispersion, as discussed in *Saturated Zone Flow and Transport Process Model Report* (CRWMS M&O 2000bn, Section 3.2.4.4). Figure 4-135 shows estimated dispersivity as a function of length scale. The dispersivity values determined for the C-Wells reactive tracer experiment (CRWMS M&O 2000bn, Section 3.1.3.2), shown as a black diamond, illustrate a trend toward larger dispersion coefficients for transport over longer distances. Solutes encounter larger-scale heterogeneities at greater distances, and thus spreading is more pronounced. There is uncertainty in this estimate due to uncertainty in the exact flow paths taken by a tracer during the test. Nevertheless, the estimate falls within the range of values from other sites, suggesting that transport in the fractured tuffs exhibits similar dispersive characteristics. The values used in the simulations of radionuclide transport are somewhat higher than those estimated from the C-Wells because of the

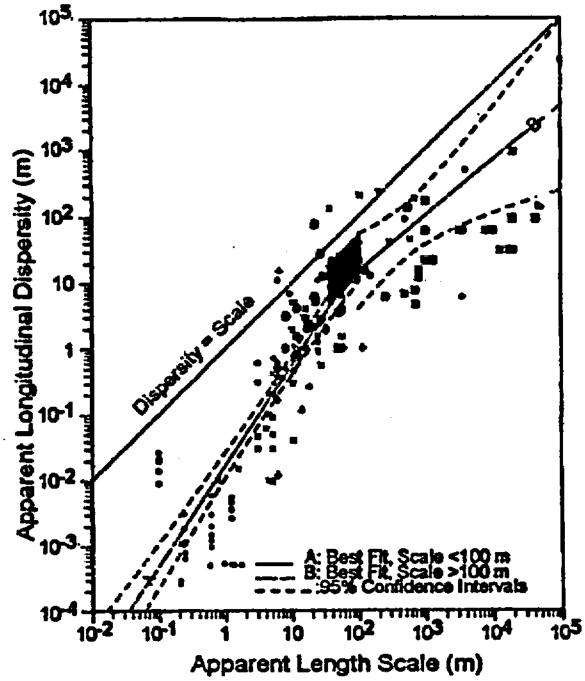


Figure 4-135. Estimated Dispersivity as a Function of Length Scale
The black diamond represents the dispersivity determined for the C-Wells reactive tracer experiment. Source: CRWMS M&O 2000eb, Figure 100.

larger scale that is relevant for radionuclide migration to the receptor location. A discussion of the numerical and field studies used to set transverse dispersivities is presented in *Saturated Zone Flow and Transport Process Model Report* (CRWMS M&O 2000bn, Section 3.7.2).

Dispersivities—The dispersion coefficient is a function of dispersivity and flow velocity and determines the rate that the contaminant plume spreads within a medium. Dispersivity has been shown to increase as a function of observation scale, attributed mainly to mixing as more heterogeneities are sampled at larger scales (Gelhar et al. 1992). Field measurements show that the transverse dispersivity is significantly less than longitudinal dispersivity (Fetter 1993, pp. 65 to 66).

In transport simulations, longitudinal dispersion results in earlier arrival but generally lower concentration. Given this behavior, no simple conservative bound exists for the longitudinal dispersion. A distribution consistent with the dispersivity-versus-scale correlation of Neuman (1990) is used in TSPA calculations. Transverse dispersion acts only to reduce concentration, with generally little effect on contaminant breakthrough time.

For comparison with regulations, concentrations are computed by dividing all the mass crossing into the accessible environment by a specified volume of water. For this reason, hydrodynamic dispersion is not expected to play an important role in saturated zone transport simulations at Yucca Mountain.

Decay Chains—The plutonium-239 decay chain (plutonium-239 → uranium-235 → protactinium-231) is particularly important because the uranium-235 daughter has significantly smaller K_d values compared to its plutonium-239 parent (CRWMS M&O 2000c, Section 3.11.2.6). This decay chain includes only the most important radioactive chain members and omits daughters with short half lives. The neptunium-237 decay chain (neptunium-237 → uranium-233 → thorium-229) has also been evaluated. The daughter contribution is less than 2 percent at 1 million years (CRWMS M&O 2000ea, Section 6.13.1.2). As such, daughter contributions to neptunium-237 transport are relatively insignificant.

Matrix-Diffusion Coefficients—The effective matrix-diffusion coefficient, which is the product of the molecular diffusion coefficient, tortuosity, and porosity, is used to account for rock geometry effects on matrix diffusion. The matrix diffusion coefficient determines the rate of contaminant flux between the matrix and the fracture. Tortuosity, a measure of deviation from straight flow path through porous medium, is a parameter that reflects the effect of the geometry of the pore structure on the flow within the matrix (it varies between zero and one). The concepts of porosity and molecular diffusion in the matrix are discussed in Section 4.2.9.1.

Experimental data on the tortuosity distribution in the various hydrogeologic units at Yucca Mountain were supplemented by an approach using porosity values to approximate tortuosity (CRWMS M&O 2000ea, Section 6.1.2.4). Tortuosity measurements on devitrified tuffs showed good agreement with this approximation.

Distribution parameters for matrix diffusion coefficients (see Table 4-25 in Section 4.2.8.2.2) are based on the measured diffusion coefficients of tritium and technetium (CRWMS M&O 2000eb, Section 6.6.1.3). The cationic (positively charged and sorbing) radionuclides are assigned values representative of the coefficient for tritium. Based on measured diffusion behavior of cationic radionuclides, this is conservative (CRWMS M&O 2000eb, Section 6.6.1.3). The anionic radionuclides (negatively charged) are assigned values representative of the coefficient for technetium, which (as pertechnetate, the predominant aqueous species of technetium) is approximately 10 times lower than that for tritium. Anionic radionuclides are more likely to be excluded from the matrix pores, which are also negatively charged.

4.2.9.2.4 Sorption

Sorption reactions are chemical reactions that involve the attachment of dissolved chemical constituents to solid surfaces. Although these reactions can be complex in detail, they are typically represented in transport calculations by a constant called the sorption coefficient (CRWMS M&O 2000bn, Section 3.2.4.3).

In the case of the Yucca Mountain flow system, an important performance assessment goal is the prediction of radionuclide transport rates to the receptor location. Radionuclide sorption onto either fracture or matrix surfaces will decrease radionuclide transport rates.

Sorption in Fractured Tuff—Sorption reaction interactions can potentially occur on the surfaces of fractures and within the rock matrix. However, because of a lack of data and to be conservative, sorption on fracture surfaces is neglected, and only sorption within the matrix is included in the saturated zone process models and the TSPA simulations. For the C-Wells field experiments, analogue tracers were used in place of radionuclides because of environmental considerations. The experiment's reactive tracer, lithium (an analogue for a sorbing radionuclide), was modeled using a matrix-diffusion model with the sorption coefficient of the matrix as an adjustable parameter (CRWMS M&O 2000bn, Section 3.1.3.2). The matrix sorption coefficient that fit the data agreed quite well with the value determined in laboratory sorption tests, thus providing an additional degree of confidence in the matrix-diffusion model. The fact that the early breakthrough of lithium had the same timing as that of the nonsorbing tracers, but with a lower normalized peak concentration, is consistent with matrix diffusion followed by sorption in the matrix.

Transport parameters obtained from the model fits for the saturated zone, with the exception of lithium sorption parameters, are listed in Table 4-28 for the Bullfrog and Prow Pass tuff tests. Further discussion of how these parameters were obtained and how they compare with other studies is provided in *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (CRWMS M&O 2000eb, Section 6.9).

Lithium sorption parameters were deduced from the field tracer tests. In these tests, lithium sorption always was approximately equal to or greater than the sorption measured in the laboratory (CRWMS M&O 2000bn, Table 3-5). Details of the methods used to obtain the field lithium sorption parameters and discussions of possible alternative interpretations of the lithium responses are provided in Reimus et al. (1999). Microsphere filtration and detachment rate constants deduced from these tracer tests are provided in *Saturated Zone Colloid-Facilitated Transport* (CRWMS M&O 2000ei, Section 6.1.2).

Experimental sorption coefficients (K_d values) were obtained using rock samples collected from the Topopah Spring welded and Calico Hills nonwelded hydrogeologic units at Busted Butte. The fine particles produced during sample crushing were not removed during the Busted Butte sorption study (CRWMS M&O 2000eb, Section 6.8.5.1.2.2) to duplicate in situ conditions, whereas fine materials were removed in the standard batch-sorption tests. Values for K_d could be influenced by small crushed-rock sizes used for sorption measurement, with the fine materials generating large K_d values. The Busted Butte transport tests are discussed in more detail in *Unsaturated Zone Flow and Transport Model Process Model Report* (CRWMS M&O 2000c, Section 3.11.11.2), *Radionuclide Transport Models Under Ambient Conditions* (CRWMS M&O 2000ea, Section 6.10), and *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (CRWMS M&O 2000eb, Section 6.8).

Table 4-28. Transport Parameters Deduced from Bullfrog Tuff and the Prow Pass Tuff Tracer Tests

Parameter (units)	Bullfrog Tuff		Prow Pass Tuff
	Pathway 1[a]	Pathway 2[b]	
Mass Fraction in Pathway (unitless)	0.12	0.59	0.75
Residence Time, Linear Flow (hr)	37	995	1230
Longitudinal Dispersivity, Linear Flow (m)	5.3	18.8	23.1
Residence Time, Radial Flow (hr)	31	640	620
Longitudinal Dispersivity, Radial Flow (m)	3.6	10.7	6.3
Effective Flow Porosity, Linear[c] (unitless)	0.0029	0.026	0.0068
Effective Flow Porosity, Radial[c] (unitless)	0.0025	0.017	0.0034
Effective Matrix-Diffusion Mass Transfer Coefficient[d] ($sec^{-1/2}$)	0.00158	0.000458	0.000968

NOTES: [a] Pathway 1 refers to pathways that resulted in the first tracer peak.
[b] Pathway 2 refers to pathways that resulted in the second peak.
[c] Based on flow log information, it was assumed that 75 percent of the production flow contributed to the Pathway 1 responses and 25 percent of the flow contributed to the Pathway 2 responses.
[d] The value of the parameter for pentafluorobenzoate (PFBA) was assumed to be 0.577 times that for bromide.
Source: Adapted from CRWMS M&O 2000eb, Tables 51 and 52.

Sorption data for the saturated zone were also determined during batch experiments, and selected results of those tests are presented in Table 4-29.

Sorption in the Alluvium—In contrast to the fractured tuffs, there are no field-scale tracer transport tests as of yet in the alluvium south of Yucca Mountain to confirm the validity of the sorption coefficient data. Tracer testing activities are underway in the Alluvium Testing Complex. However, transport of sorbing solutes in porous media not controlled by fractures has been well studied (CRWMS M&O 2000bn, Section 3.2.4.3), and it is reasonable to assume that the transport velocities of sorbing radionuclides in the alluvium can be conservatively represented using an equilibrium sorption coefficient. Sorption onto alluvium from the Nye County Early Warning Drilling Program wells has been measured for a few key radionuclides (CRWMS M&O 2000eb, Section 6.4.5). For the remaining radionuclides, sorption coefficients are estimated based on values measured for crushed tuff (CRWMS M&O 2000eb, Section 6.9.3.3).

4.2.9.2.5 Colloid-Facilitated Transport

Colloid-Facilitated Transport Experiments—Figure 4-136 provides a conceptual illustration of colloid-facilitated transport processes. Colloids in the saturated zone are capable of facilitating the transport of radionuclides over long distances if (1) a large percentage of the colloids do not irreversibly filter or attach to surfaces of subsurface materials and (2) radionuclide desorption rates from the colloids are slow (i.e., radionuclides are strongly sorbed to colloids), or if (3) colloid concentrations are so high that colloid surfaces can effectively compete with immobile surfaces for radionuclides. However, analyses of colloid

Table 4-29. Sorption-Coefficient Distributions for Saturated Zone Units From Laboratory Batch Tests

Element	Rock Type	K_d (mL/g)			
		Minimum	Maximum	Mean	Coefficient of Variation
Americium	Devitrified	100	2000	N/A	N/A
	Vitric	100	1000	400	0.20
	Zeolitic	100	1000	N/A	N/A
	Iron oxide	1000	5000	N/A	N/A
Neptunium	Devitrified	0	2.0	0.5	0.3
	Vitric	0	2.0	0.5	1.0
	Zeolitic	0	5.0	1.0	0.25
	Iron oxide	500	1000	N/A	N/A
	Alluvium	0	100	18	1.0
Plutonium	Devitrified	5	100	50	0.15
	Vitric	50	300	100	0.15
	Zeolitic	50	400	100	0.15
	Iron oxide	1000	5000	N/A	N/A
Uranium	Devitrified	0	5.0	N/A	N/A
	Vitric	0	4.0	N/A	N/A
	Zeolitic	5	20.0	7.0	0.3
	Iron oxide	100	1000	N/A	N/A
	Alluvium	0	8.0	N/A	N/A
Chlorine, Technetium, Iodine	All tuffs	0	0	N/A	N/A
Technetium	Alluvium	0.27	0.62	N/A	N/A

NOTES: N/A = not applicable. Source: CRWMS M&O 2000eb, Table 2b.

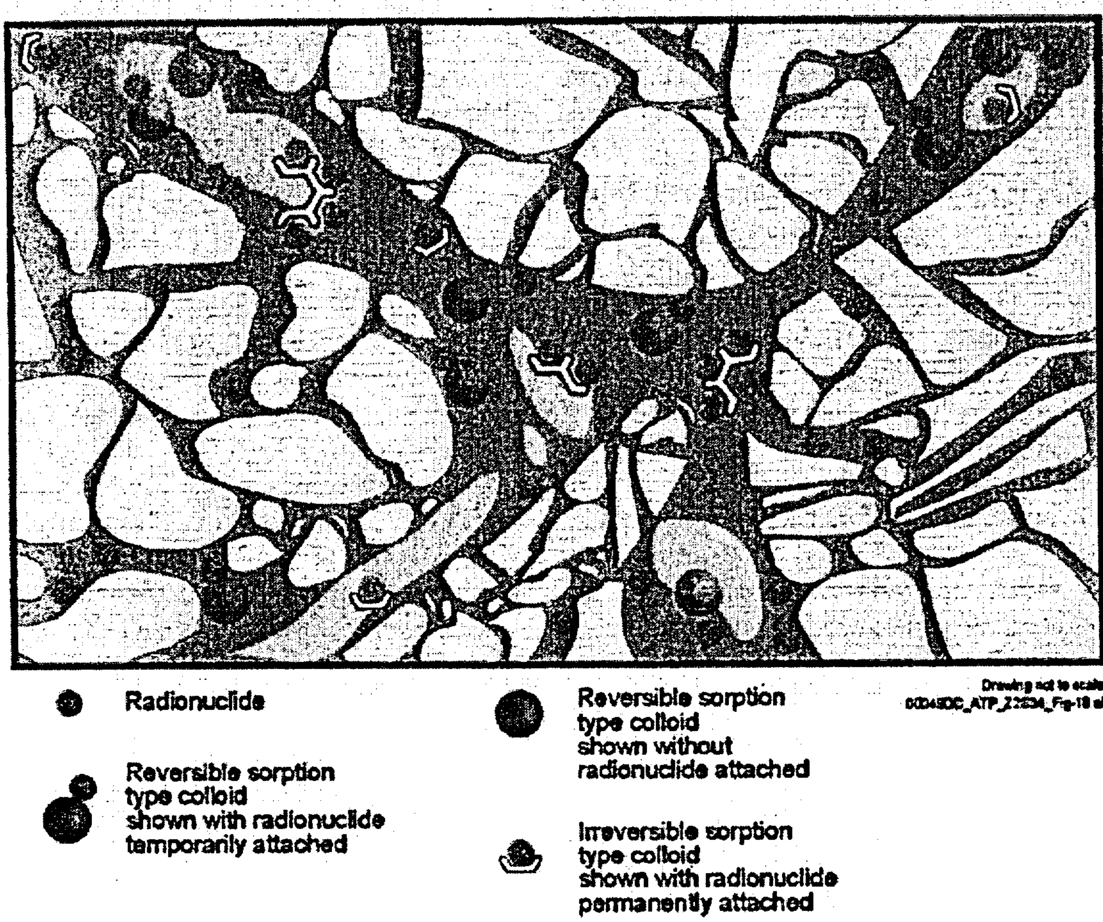


Figure 4-138. Colloid-Facilitated Transport
Colloids are small particles ranging from 0.1 to 5 µm (0.000004 to 0.0002 in.) in diameter. Some radionuclides are sorbed to colloids and thereby transported in groundwater. Source: CRWMS M&O 2000a, Figure 3.7-6.

concentrations and size distributions in Yucca Mountain groundwater have not found high concentrations of colloids. Published correlations of colloid concentrations as a function of water chemistry, which draw upon a global database of measurements, also suggest that colloid concentrations are unlikely to be high enough for the third condition to be met even under perturbed conditions (Triay, Degueldre et al. 1996).

The DOE has addressed the filtering or attachment of colloids to surfaces of subsurface materials using polystyrene microsphere data from the C-Wells field tests to obtain conservative estimates of colloid attachment and detachment rates in fractured tuffs. The DOE also has used published data to obtain bounding estimates of attachment and detachment rates in alluvium (CRWMS M&O 2000bn, Section 3.2.4.5.3). The published correlations of colloid concentrations as a function of water chemistry also support indirect estimates of attachment rates, as it is widely accepted that lower concentrations occur under conditions in which colloids are less stable and, hence, more likely to attach to surfaces. Details of stability-based arguments for bounding colloid concentrations and attachment rates in Yucca Mountain waters are provided in *Colloid-Associated Radionuclide Concentration Limits: ANL* (CRWMS M&O 2000dt, Section 6).

Recent laboratory experiments focused on addressing the magnitude and reversibility of radionuclide sorption onto colloids. Some of the earliest laboratory experiments involved the transport of cesium-137 and silica colloids in columns packed with glass beads. Cesium sorption to the silica was fast and reversible, and it was shown that under these conditions, the ability of the colloids to facilitate cesium-137 transport was limited because of the large amount of competing sorptive surface area presented by the glass beads. Nevertheless, these experiments helped establish equilibrium- and kinetic-based modeling approaches for describing colloid-facilitated transport in the saturated zone. These experiments also made it clear that considerable colloid-facilitated transport would only be an issue for radionuclides that sorbed to colloids more strongly than did cesium-137.

Further laboratory experiments focused on measurements of the magnitude and rates of sorption and desorption for strongly sorbing, long-lived radionuclides onto several different types of colloids that may be present in the near-field (iron oxides such as goethite and hematite that might result from degradation of waste package materials) or in the far-field (silica, montmorillonite clay) environment at Yucca Mountain (CRWMS M&O 2000bm, Section 3.8). These studies used the radionuclides plutonium-239 and americium-243, with the plutonium being prepared in two different forms: colloidal plutonium (IV) and soluble plutonium (V). Also, water from Well J-13 and a synthetic sodium-bicarbonate solution have been used in the experiments. Colloid concentrations were varied in some of the experiments to determine the effect of colloid concentration. Details of the experiment and summaries of the plutonium-239 sorption and desorption rates onto the different colloids are provided in *Colloid-Associated Radionuclide Concentration Limits* (CRWMS M&O 2000dt). The results can be summarized as follows:

- The sorption of plutonium-239 onto hematite, goethite, and montmorillonite colloids was strong and rapid, but the sorption of plutonium-239 onto silica colloids was slower and not as strong.

- The desorption rates of plutonium-239 from hematite colloids were so slow that they are essentially impossible to measure after 150 days. Desorption from goethite and montmorillonite colloids was also slow, but not as slow as for hematite. The desorption rates of plutonium-239 from silica colloids was rapid relative to the other colloids studied.

- For a given form of plutonium-239, sorption was generally stronger, faster, and less reversible in the synthetic sodium-bicarbonate water than in the natural Well J-13 water. Apparently, the presence of other ions, probably most notably calcium, in the natural water tended to suppress slightly the sorption of plutonium-239.

- There was no clear trend of colloidal plutonium (IV) or soluble plutonium (V) being more strongly sorbed to the colloids. In general, it appeared that plutonium (V) was sorbed slightly more to hematite and silica, while plutonium (IV) was sorbed slightly more to goethite and montmorillonite.

- The sorption of plutonium-239 was greatest per unit mass of colloid at the lowest colloid concentrations, which implies that the most conservative K_d values for performance assessment will come from sorption data generated at low colloid concentrations.

The sorption of americium-243 onto hematite, montmorillonite, and silica colloids showed the same trends as plutonium-239 sorption (i.e., for both americium-243 and plutonium-239, sorption onto hematite was stronger than sorption onto montmorillonite, and sorption onto montmorillonite was stronger than it was for silica), and the magnitudes of sorption for the two radionuclides were similar for the different colloids.

This ongoing work indicates:

- Waste form colloids such as hematite pose the greatest risk for colloid-facilitated transport, although these colloids would have to travel through the unsaturated zone before reaching the saturated zone.

- Natural clay colloids will facilitate plutonium or americium transport more than silica colloids in the saturated zone.

4.2.9.2.6 Analogues to Saturated Zone Radionuclide Transport

In this section, natural analogue studies conducted in saturated environments are reviewed. These sites occur around the world in uranium ore deposits and rare-earth deposits in different types of host rocks (Figure 4-137). Characteristic of these sites is the presence of redox fronts (e.g., Poços de Caldas and Oklo) or weathering and periodic influx of oxidizing water (e.g., Alligator Rivers and Poços de Caldas). Although Cigar Lake applies to reducing groundwater that is not relevant to conditions at Yucca Mountain, localized oxidation may have resulted from radiolysis and could be useful. Additional details of these and other sites are presented in *Saturated Zone Flow and Transport Process Model Report* (CRWMS M&O 2000bn, Section 3.4.5).

Nevada Test Site (CRWMS M&O 2000bn, Section 3.4.5.3.3)—There is some field evidence of colloid-facilitated transport of radionuclides at the Nevada Test Site. Plutonium was detected in groundwater from a well on the Test Site. The isotope ratio of plutonium-240 to plutonium-239 showed that the plutonium had originated from an underground test detonated in the saturated zone. The results indicated that plutonium had transported more than 1.3 km (0.8 mi) over a 30-year period, although plutonium is strongly sorbing at the Nevada Test Site and assumed to be immobile (Kersting et al. 1999). Filtration of the groundwater samples showed that the plutonium was attached to colloidal material in the water. However, it should be noted that the plutonium observed in this study originated from an underground nuclear bomb test and the effects of the blast itself on plutonium transport are not fully understood. Other evidence suggests that transport rates in the saturated zone are significantly lower than would be inferred from the distance travelled by the plutonium.

Colloid concentrations have been measured in several groundwater samples from Yucca Mountain and from other areas at the Nevada Test Site. The measured particle concentrations vary between 1.05×10^6 and 2.72×10^{10} particles per milliliter, with the lowest being for water from Well J-13 and the highest for water from Well U19q on Pahute Mesa (CRWMS M&O 2000ec, Section 6.2.2.2). These values are consistent with what has been reported in the literature for various groundwaters

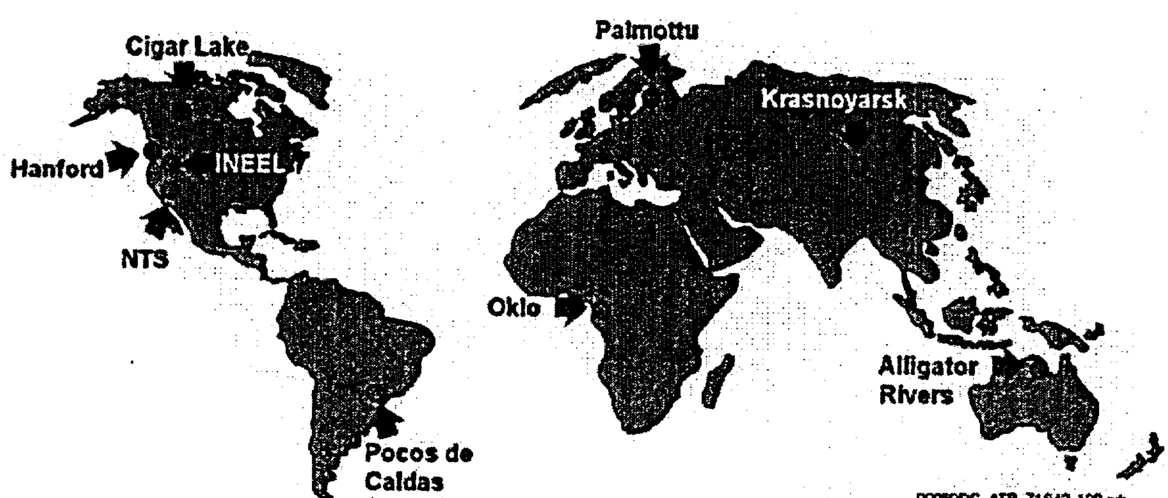


Figure 4-137. Natural Analogue Sites Used for Comparison with Yucca Mountain
INEEL = Idaho National Engineering and Environmental Laboratory; NTS = Nevada Test Site. Source: CRWMS M&O 2000bn, Figure 3-26.

around the world. In the Pahute Mesa drainage, Buddemeier and Hunt (1988, p. 537) found colloid concentrations of 0.8 to 6.9 mg/L for particles greater than 30 nm (0.000001 in.) in size.

Poços de Caldas, Brazil (CRWMS M&O 2000bn, Section 3.4.5.2.2)—The Poços de Caldas caldera in Brazil was the focus of a study involving the Osamu Utsumi mine (a uranium ore body with subsidiary thorium, zirconium, and rare-earth element enrichment) and Morro do Ferro (a thorium and rare-earth element ore body with subsidiary uranium). This site is important as a saturated zone analogue for sorption in alluvium and onto fracture coatings, for matrix diffusion, and for colloidal transport. The Osamu Utsumi uranium mine is known for a well-developed redox front in the uranium ore, and the primary mineralization is mostly low-grade and dispersed throughout the rock. The redox front generally is sharp but irregular in profile as it follows the dips of faults and fractures along which oxidizing waters have penetrated. Uranium mineralization occurs at the redox front itself. At Morro do Ferro, the ore occurs in elongated mineralized lenses. The groundwater at Osamu Utsumi has high concentrations of uranium (up to 10 mg/L), but those at Morro do Ferro are lower. Thorium-232 concentrations generally are low in groundwater from both sites (less than 0.1 µg/L). Most colloids are composed of iron and organic species. Only minor amounts of uranium are associated with colloids, but thorium and rare-earth elements are transported in the colloidal fraction.

Oklo, Gabon (CRWMS M&O 2000bn, Section 3.4.5.2.3)—The Oklo uranium mine in Gabon contains the only known examples of natural fission reactors, and 14 reactor zones have been identified among 3 uranium deposits (see Section 4.3.2.1). This site is important as a saturated zone analogue for sorption in alluvium and onto fracture coatings and for matrix diffusion. At this site, low-grade ore contains 0.1 to 1.0 percent uranium oxide, whereas high-grade ore contains up to 10 percent uranium oxide. High-grade ore occurs within fractures in sandstone rocks. The formation of high-grade ore is attributed to the remobilization of low-grade ore by oxidizing hydrothermal fluids, which transported the uranium along faults, followed by precipitation in fractures when conditions became more reducing.

Alligator Rivers, Australia (CRWMS M&O 2000bn, Section 3.4.5.2.1)—The Alligator Rivers Analogue Project in Australia was conducted to investigate the migration of radionuclides from an enriched uranium deposit. Leaching of primary ore resulted in the formation of four distinct zones: unaltered primary ore; a uranium silicate zone formed by in situ alteration of the primary ore; a zone of secondary uranyl phosphate minerals that are currently being leached by groundwater; and a zone with uranium in association with clays and iron oxyhydroxides. Dissolved uranium is transported from the uranium oxide zone at depth to the silicate zone, also at depth, then upward to the phosphate zone. The uranyl phosphate zone exists near the surface in the most oxidized weathered zone. A dispersion fan occurs in the weathering zone where uranium has been mobilized, and secondary minerals are found as far as 50 m (160 ft) downstream from the ore body, with detectable concentrations of uranium-series nuclides for about 300 m (1,000 ft) downstream in the dispersion fan. Groundwater samples taken from boreholes were studied with respect to their colloidal contents. Boreholes closest to faults had the greatest variety of colloids. The colloids identified included particles of iron, kaolinite, chlorite, silica, lead, uranium, and titanium. All colloid samples were dominated by iron-rich particles, and uranium was only found in iron-rich species. Low colloid concentrations (about 10^6 particles per liter or less) and the absence of radionuclides in colloids outside the center of the ore body indicated little colloidal transport of radionuclides at this site.

4.2.9.3 Saturated Zone Flow and Transport Process Model Development and Integration

To provide the basis for the analysis of radionuclide transport from the water table beneath the potential repository to the point of regulatory compliance, a numerical site-scale saturated zone flow model was developed to simulate groundwater flow in the area of the potential repository. The flow model is a steady-state model that is calibrated to represent current groundwater flow conditions in the Yucca Mountain area. A continuum approach for simulating groundwater flow through the fractured rock and alluvial materials is adopted in this model. This approach allows the use of widely accepted mathematical equations describing groundwater flow through porous medium as the mathematical basis for the model. A numerical solution to these equations is obtained using the FEHM code (Zyvoloski et al. 1997a). FEHM uses a method that has been used extensively in petroleum reservoir engineering, the control-volume finite element method, to obtain the numerical solution (Forsyth 1989).

Flow Model Development—The area selected as the domain of site-scale saturated zone flow model is shown in Figure 4-138. The model domain covers an area of approximately 1,350 km^2 (521 mi^2) and is 45 km (28.0 mi) long by 30 km (18.6 mi) wide. The model domain extends to a depth of approximately 2,750 m (9,020 ft) below the interpreted water table. A number of criteria were used to establish the model domain. The model area was made sufficiently large to minimize the effects of the boundary conditions on the estimated permeability values and simulated flow paths at Yucca Mountain, to assess groundwater flow and contaminant transport at the regulatory compliance points downgradient from the potential repository area, and to include wells in the Amargosa Desert at the southern end of the modeled area. However, the area was selected to be small enough to minimize the number of nodes required in the computational grid. The thickness of the model was established to include part of the regional Paleozoic carbonate aquifer (CRWMS M&O 2000bn, Section 3.2.1).

A structured computational grid using orthogonal hexahedral elements was developed for the site-scale saturated zone flow and transport model (Figure 4-139). A horizontal grid spacing of 500 m (1,640 ft) was selected based on previous modeling studies, which demonstrated that this grid spacing provided sufficient horizontal resolution for the model. Although a uniform horizontal spacing was adopted, a nonuniform vertical spacing was established to provide the resolution necessary for accurately representing flow and transport along critical flow and transport pathways in the saturated zone. A finer grid spacing was adopted for shallower portions of the model (10 m [33 ft]) near the water table, and a progressively coarser grid was adopted for deeper portions of the aquifer (550 m [1,800 ft]) at the bottom of the model domain (CRWMS M&O 2000bn, Section 3.3.5.1).

The physical hydrogeologic unit present at each node in the site-scale saturated zone flow model grid was identified using the three-dimensional hydrogeologic framework model (USGS 2000d). The hydrogeologic framework model was constructed using available data from the Death Valley regional flow model (D'Agnese, Faunt et al. 1997), geologic maps and cross sections, borehole data, geophysical data, digital elevation data, and the previously developed geologic framework model for the immediate 40-km^2 (15-mi^2) potential repository area. Geologic units were classified into hydrogeologic units based on their hydraulic properties and lateral extent. A basic principle followed is that the hydrogeologic units at Yucca Mountain form a series of alternating volcanic aquifers and confining units overlying the regional carbonate aquifer. To represent the stratigraphy at a level of detail that would allow a computationally efficient flow model at reasonable computation times, the geologic units are simplified based on their general hydrologic properties. In all, a complex three-dimensional spatial pattern of hydrogeologic units was delineated in the site-scale saturated zone flow and transport model area (Figure 4-140) (CRWMS M&O 2000bn, Section 3.2.1).

Development of a numerical flow model requires specification of boundary conditions for the model domain (CRWMS M&O 2000bn, Section 3.3.5.3). Fixed-head boundary conditions were established around the periphery of the computational grid based on the water levels identified on the potentiometric map previously developed for the site-scale model area (Figure 4-141). The constant head identified for each node was applied uniformly through each layer of the model. In spite of such "constant-head" boundary conditions, vertical gradients develop internally in the model domain in response to geohydrologic conditions, and the calibrated model is capable of representing the upward vertical gradients observed between the carbonate aquifer and overlying volcanic aquifers

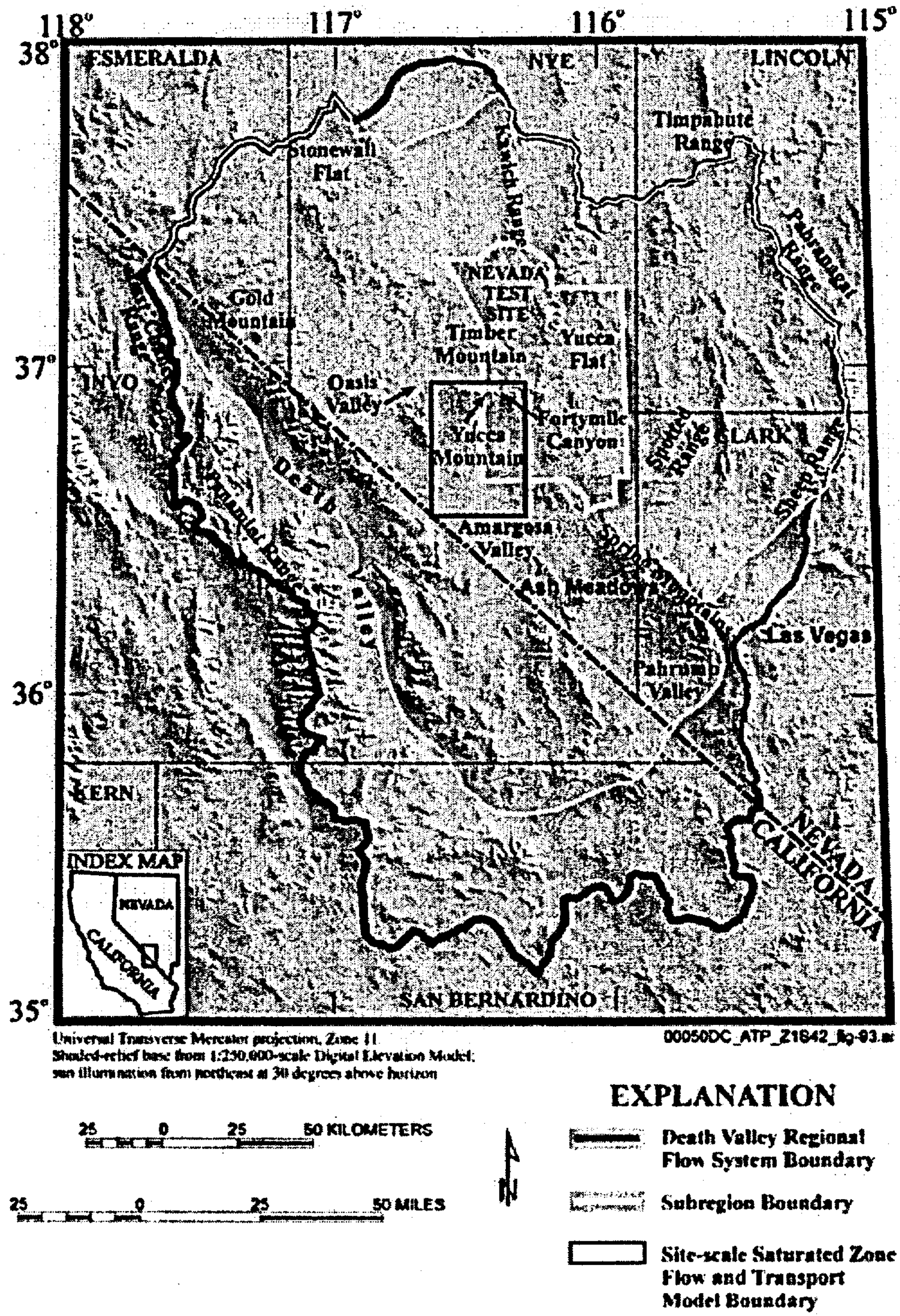


Figure 4-138. Domain of Site-Scale Saturated Zone Flow and Transport Model for the TSPA-SR
The Death Valley regional flow system is the model domain of the regional model used to provide the site-scale flow and transport model with the boundary conditions and to simulate future climate changes. Source: CRWMS M&O 2000bn, Figure 2-1.

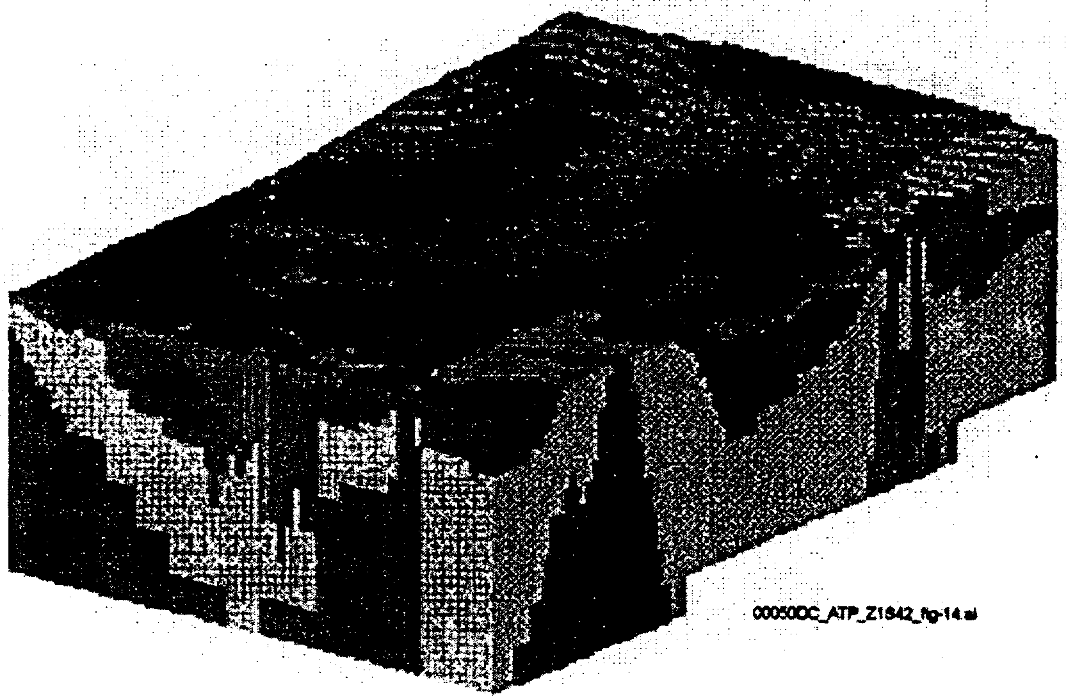


Figure 4-139. Computational Grid Developed for the Site-Scale Saturated Zone Flow and Transport Model
This representation of the computational grid illustrates the complex three-dimensional spatial relation among the units within the site-scale model area. Colors represent different hydrogeologic units. Grid cells are 500 m on each side in the north–south and east–west directions, and the cells vary in depth from about 10 m to about 550 m. Source: CRWMS M&O 2000bn, Figure 3-18.

(CRWMS M&O 2000ej, Section 6.1.2). A no-flow boundary was established at each node located along the bottom of the computational grid. Although flow conditions in the deeper portions of the model domain are not well established, the depth of the bottom boundary is such that this boundary condition is not likely to exert an important influence on flow at shallower levels where groundwater flow and transport is of greater interest to the performance assessment. At the top of the model, a flux boundary condition was established to represent recharge to the system (Figure 4-142).

Representative hydrologic properties were assigned for each node in the computational grid. For flow modeling, these properties include permeability, porosity, and viscosity. Permeability values were assigned to each node during model calibration (Figure 4-143). Because steady-state flow is simulated in site-scale saturated zone flow, the specific storage values assigned at each node does not influence the water levels predicted by the model (CRWMS M&O 2000bn, Section 3.3.5.5). However, to facilitate the calculation of the specific discharge, which is the volume of water flowing through a unit area of rock at unit time, a porosity value of 1.0 was assigned to all nodes. Because the viscosity of groundwater depends on temperature, the nodal values for viscosity were assigned based on the expected temperature distribution in the subsurface.

4.2.9.3.1 Limitations and Uncertainties

In any numerical simulation of a physical process using a mathematical model, assumptions are made and limitations apply (CRWMS M&O 2000bn, Section 3.5). The following sections discuss the critical assumptions and limitations of the site-scale saturated zone flow and transport model and the parameters that are used as input in this model. Many of the parameter values used in the model are estimated using simple mathematical models.

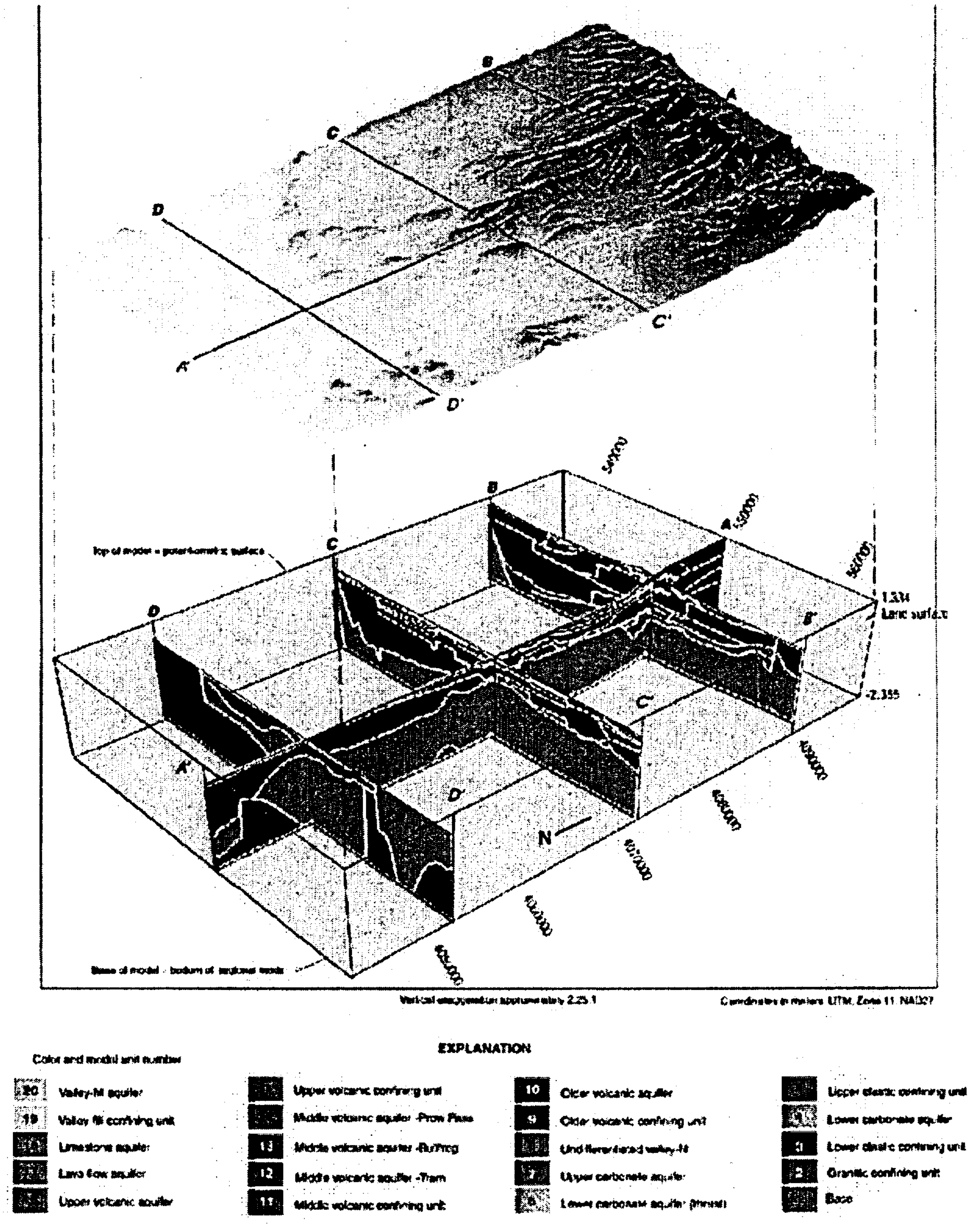
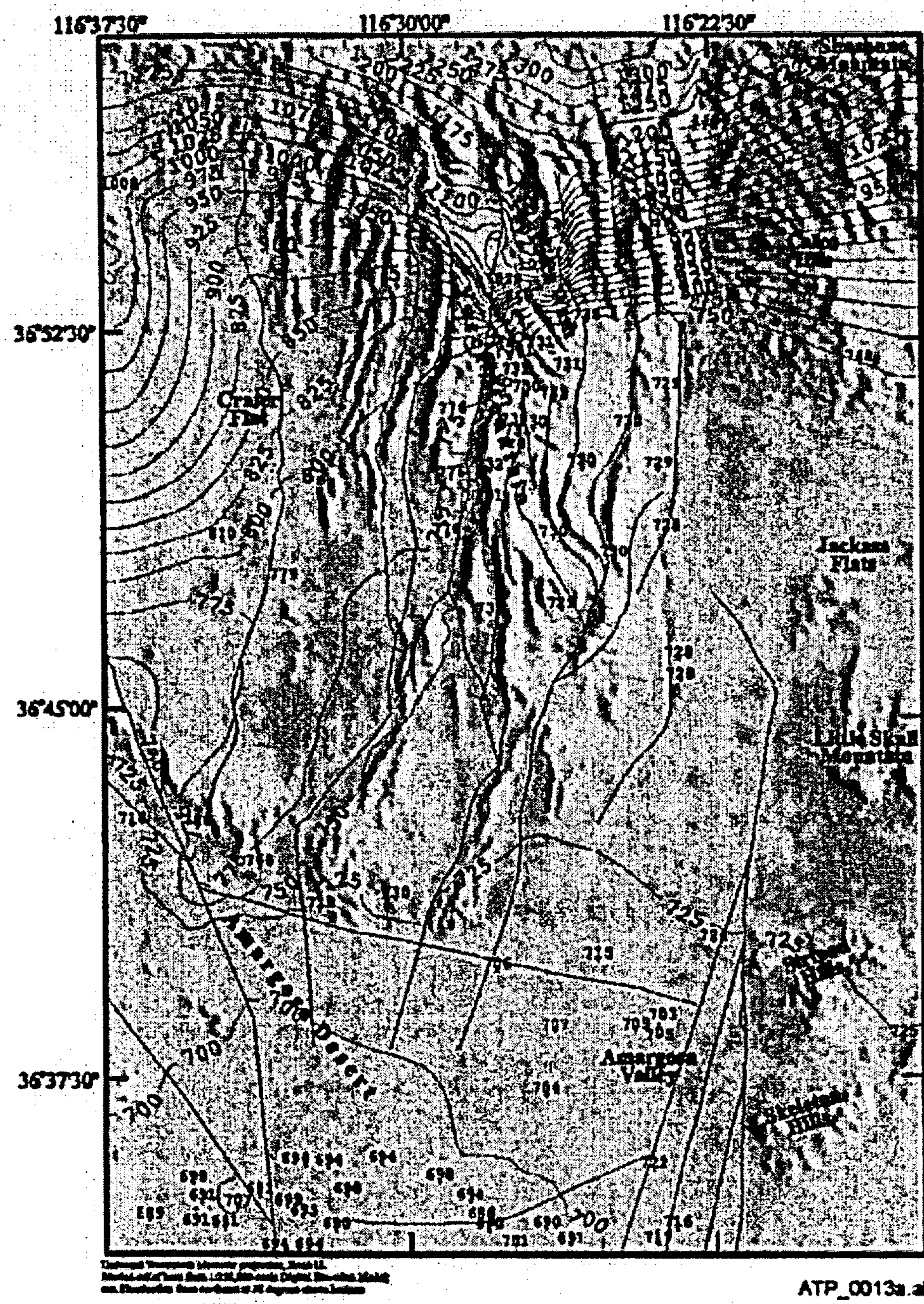


Figure 4-140. Complex Spatial Pattern of Hydrogeologic Units Depicted as a Fence Diagram
Source: CRWMS M&O 2000bn, Figure 3-13.



EXPLANATION

— Tertiary faults

— Potentiometric contour - Shows altitude of potentiometric surface. Contour interval 25 meters. Datum is sea level.

Observation well. Water-level altitude (m).

ATP_0013a.ai

0 2 4 6 8 10 KILOMETERS

0 2 4 6 8 10 MILES

Figure 4-141. Site-Scale Saturated Zone Model Area, Showing Potentiometric Surface Contours, Water Level Altitudes, and Tertiary Faults

Source: USGS 2000d, Figure 6-2.

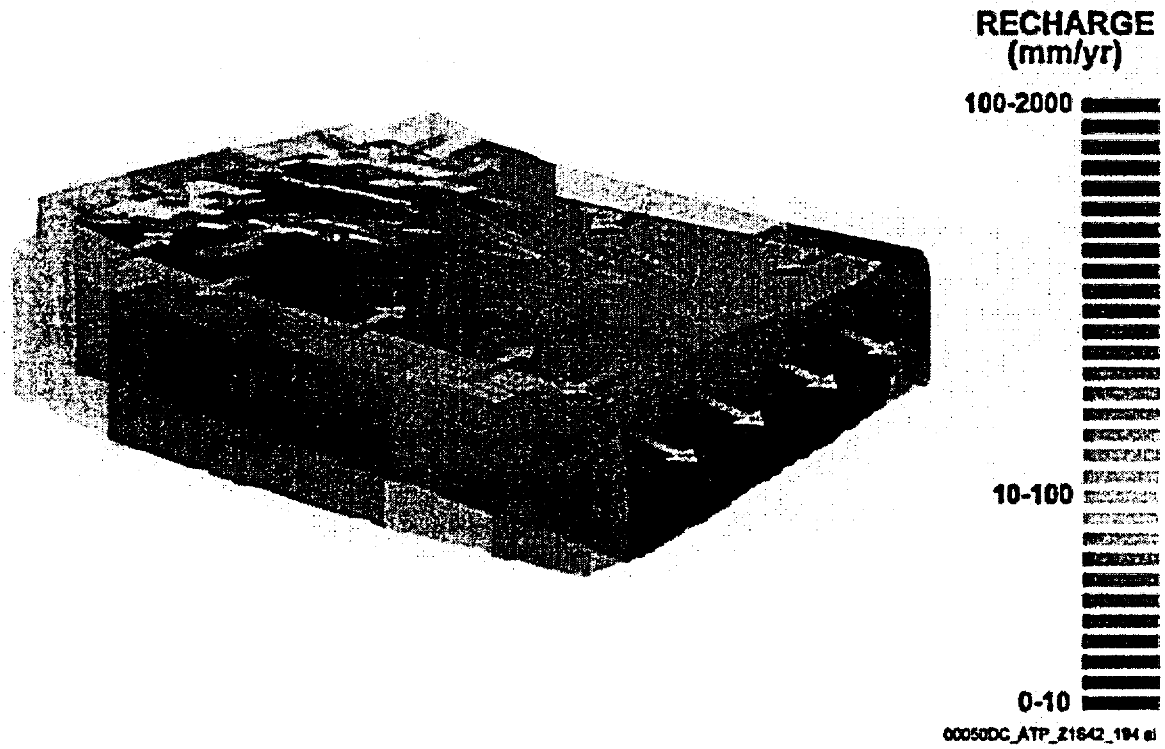


Figure 4-142. Lateral and Top Boundary Conditions for the Three-Dimensional Saturated Zone Flow Model for the Present-Day Climate
Source: CRWMS M&O 2000a, Figure 3.8-6.

Other parameter values may be estimated from data. However, extracting model parameter values from data is often not straightforward, and statistical methods that require extrapolation or corrections are used. Assumptions embedded in these methods influence the estimated individual parameter values and are described in the analysis and model reports. For example, stochastic parameters and their associated uncertainty distribution are presented in *Uncertainty Distribution for Stochastic Parameters* (CRWMS M&O 2000ck).

Taken in total, these data provide an appropriate and adequate basis for the conceptual model and numerical model of the site-scale saturated zone flow and transport system (CRWMS M&O 2000bn, Section 3.5). The site characterization information, along with inferences based on that information, support a conceptual model in which groundwater flow is controlled by the spatial distribution of geologic units and structural features. Site-specific data, together with regional-scale studies, suggest that a large fraction of groundwater flowing in the saturated zone enters the Yucca Mountain site area as lateral flow from the north with a small fraction contributed by recharge near Yucca Mountain. The conceptual model of radionuclide transport in fractured rocks includes the processes of advection, dispersion, matrix diffusion, sorption, and colloid-facilitated transport, as supported by site data. These components of the conceptual model are implemented numerically in the site-scale saturated zone flow and transport model, which represents the processes relevant to radionuclide migration from Yucca Mountain to the biosphere.

Groundwater Flow Processes—Assumptions used in modeling the groundwater flow process include those of the regional-scale models and the

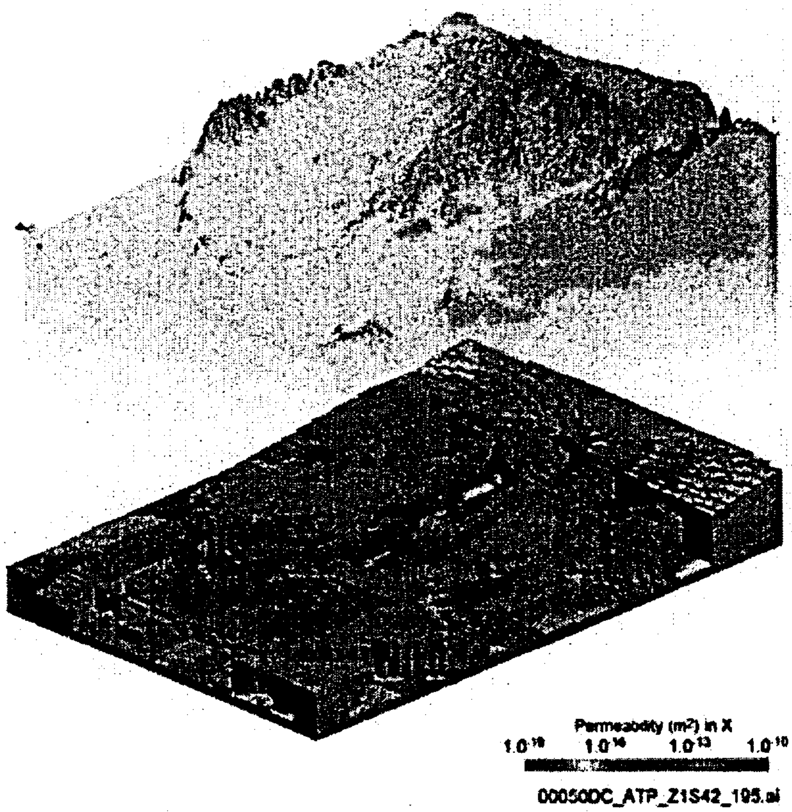


Figure 4-143. Three-Dimensional Saturated Zone Model Domain Showing the Different Permeability Fields
Permeabilities are assigned on a zone basis. Each zone represents hydrogeologic characteristics. Source: CRWMS M&O 2000a, Figure 3.8-7.

site-scale saturated zone flow and transport model and those made in estimating parameters that are used as input to these models. The following assumptions apply to the TSPA-SR continuum modeling approach (CRWMS M&O 2000el, Section 5):

- On the scale represented by the site-scale saturated zone flow and transport model, the site is well represented by a continuum flow model. The reasons for this choice rather than a discrete fracture model are discussed in detail in the section on alternative conceptual models.

- Estimates of specific discharge from the volcanic aquifer, elicited from the saturated zone expert elicitation panel, are assumed to be applicable to the entire flow path from the potential repository to the receptor location. The estimates were based primarily on data from hydraulic testing in wells in volcanic units and the hydraulic gradient inferred from water level measurements (CRWMS M&O 1998j, p. 3-8).

- Horizontal anisotropy in permeability is adequately represented by a permeability tensor that is oriented in the north–south and east–west directions. For the purposes of the TSPA nominal case, both horizontal isotropy and anisotropy are considered for radionuclide transport. Analysis of the probable direction of horizontal anisotropy shows that the direction of maximum transmissivity is N 33° E (Winterle and La Femina 1999, p. iii), indicating that the anisotropy applied on the site-scale saturated zone model grid is within approximately 30° of the inferred anisotropy.

- Horizontal anisotropy in permeability applies to the fractured and faulted volcanic units of the saturated zone system along the groundwater flow paths that run from the potential repository to points south and east of Yucca Mountain. Given the conceptual basis for the anisotropy model, it is appropriate to apply anisotropy only to those hydrogeologic units that are dominated by groundwater flow in fractures.

- Current groundwater flow conditions in the saturated zone system are at steady state. A steady-state model of the flow conditions is used to reflect the assumption that a steady-state representation of the saturated zone system is accurate. Studies by Luckey et al. (1996, pp. 29 to 32) indicate that there are no long-term consistent trends in the data from wells at Yucca Mountain.

- Changes in the water table elevation (due to future climate changes) will have negligible effect on the direction of the groundwater flow near Yucca Mountain. This assumption has been studied in regional-scale (D'Agnese, O'Brien et al. 1999) and subregional-scale (Czarnecki 1984) flow models. These studies found that the flow direction did not change significantly under increased recharge scenarios.

- Future water supply wells that might be drilled near Yucca Mountain (including outside the controlled area) will have a negligible effect on the hydraulic gradient.

- Possible effects due to temperature gradients and heat transport are assumed to be negligible. Heat transport can affect flow modeling through the temperature dependence of fluid viscosity and density.

Radionuclide Transport Properties—Radionuclide transport is modeled using a particle-tracking methodology (CRWMS M&O 2000eh). This three-dimensional particle-tracking model assumes transport along streamlines and takes into account advection, dispersion, sorption, and matrix diffusion. This particle-tracking model is semi-analytical in nature and has been developed to include anisotropic structures. Using particle tracking to model radionuclide transport using particle tracking has some advantages over numerical solutions to an advection–dispersion equation. Two of these advantages include less numerical dispersion and the ability to model plumes on a subgrid block scale. Disadvantages include the facts that computations of concentration may require the use of a large number of particles and that particles may move into zones of low advection, requiring a long time to exit. The method allows for matrix diffusion, but does not account for advective flow in the matrix, where advection is slower than in the fractures. Particles are allowed to exit the matrix through Brownian motion into the fractures, where they are transported by advection. The transport model carries the following assumptions:

- On the scale represented by the site-scale saturated zone flow and transport model, the site is well-represented by a continuous flow and transport model. In particular, the specific discharge field computed by the FEHM flow model (Zyvoloski et al. 1997b) represents the specific discharge averaged over grid cells that are 500 m (1,640 ft) long, which means that possible long (more than 500 m [1,640 ft]) high-permeability conduits would not be represented accurately by the present transport model. The possible existence of relatively long, high-permeability structural features with a north–south orientation is explicitly incorporated in the model through the inclusion of horizontal anisotropy.

- An appropriate method for scaling transport to account for increasing mass flux in response to changes in the future climate is the convolution integral method. An assumption inherent in this method is that the system being simulated exhibits a linear response to the input function. In the case of solute transport in the saturated zone system, this assumption implies, for example, that a doubling of the input mass flux results in a doubling of the output mass flux. This assumption is valid for the site-scale saturated zone flow and transport model because the underlying transport processes (e.g., advection and sorption) are linear with respect to solute mass.

- Fractures are equally spaced, smooth, and have constant aperture. The numerical representation of matrix diffusion assumes equally spaced, smooth, constant aperture fractures. The assumption that the fracture aperture width is equal to that of a flowing interval tends to underestimate fluid velocity, whereas the assumption that no flow occurs in the matrix tends to overestimate the fluid velocity in the fracture.

- Fluid in the matrix of volcanic rocks is stagnant. This assumption is conservative from the perspective of the performance of the potential repository because if mass flows in the matrix, then the mass available for faster transport and flow velocities in the flowing intervals (fractures) is reduced.

- The mathematical representation assumes linear sorption at equilibrium due to the large temporal and spatial scales involved in radionuclide transport. Furthermore, the low relative concentrations of radionuclides support this assumption (CRWMS M&O 2000eb, Section 6.4).

Modeling Limitations—The site-scale saturated zone flow and transport model is adequate for its intended purpose, which is to model groundwater flow and radionuclide transport from the potential Yucca Mountain repository to the site-scale model boundary under present day and potential future climate conditions (CRWMS M&O 2000bn, Section 3.5.4). Here, adequate means that the transport model is an internally consistent representation of the saturated zone, which is subject to considerable uncertainty due to assumptions and simplification inherent in groundwater flow and transport modeling. Both the important processes and the subprocess models that address them have been identified. Many processes are inherently uncertain, and this uncertainty is handled through the use of stochastic realizations. The site-scale saturated zone flow and transport model is not appropriate (and was not used) for the following types of simulations (CRWMS M&O 2000bn, Section 3.5.4):

- Computing transport over short distances. Over short distances (less than 1 km [0.6 mi]), transport likely is dominated by discrete fractures or fracture zones.

- Computing scenarios involving heavy well pumpage near Yucca Mountain. These scenarios would violate the conditions of a steady-state groundwater system, since they might involve large changes to the water table.

- Computing short-term transient hydrologic conditions. The site-scale saturated zone flow and transport model is not appropriate for computing short-term transient hydrologic conditions because it has not been calibrated using transient pumping tests.

- Performing analyses of the effects of certain disruptive events. Disruptive events, such as intrusive volcanic events, could affect the hydrogeologic environment at Yucca Mountain, for example, by altering the permeability field or causing transient changes to the water table. Such an analysis would require modifying the hydrogeologic framework model, regridding, or modifying other subprocess models and parameters to account for transient changes to the water table.

Process Model Uncertainty—The site-scale saturated zone flow and transport model and its components are comprehensive and complex. The model was used by TSPA-SR to characterize flow and transport processes that operate in the saturated zone below Yucca Mountain. The accuracy and reliability of predictions from the site-scale saturated zone flow and transport model are critically dependent on the accuracy of estimated model properties to which the model is sensitive, other types of input data, and conceptual models of the hydrology and geology. These models are limited mainly by the current characterization of the saturated zone system (including the geological and conceptual models), the continuum modeling approach, steady-state flow, and the available field and laboratory data.

Investigations have indicated that a large amount of variability exists in the flow and transport parameters over the spatial scale of the saturated zone flow and transport model domain. Even though considerable progress has been made in this area, the major remaining uncertainties in model parameters are: (CRWMS M&O 2000bn, Section 3.5.5):

- Transport properties, including effective porosity in the alluvium
- Sorption coefficients for different elements in the alluvial and volcanic units
- Matrix molecular diffusion in different hydrogeological units for different radionuclides
- Dispersivities in volcanic and alluvial units
- Location of the transition zone where the flow path from the potential repository to the transitions from volcanic to alluvial hydrogeological units.

Uncertainty is addressed in the analysis of the performance of the potential repository system by considering selected parameters as stochastic variables and sampling from parameter uncertainty distributions in realizations of the saturated zone. The stochastic parameter uncertainty distributions are developed from limited field and laboratory data, expert elicitation, and literature surveys. These uncertainties are addressed in Sections 3.7.1 and 3.7.2 of the *Saturated Zone Flow and Transport Process Model Report* (CRWMS M&O 2000bn), and in Section 6 of *Uncertainty Distribution for Stochastic Parameters* (CRWMS M&O 2000ek). The matrix porosity in the volcanic units, bulk density in the volcanic units and the alluvium, and temperature were not treated as probability distributions. Rather, a deterministic value was used to represent these parameters in the simulations. The deterministic values vary from node to node in the model, as taken from the Integrated Site Model. Descriptions of how each parameter is represented and associated justifications are included in Section 6 of *Uncertainty Distribution for Stochastic Parameters* (CRWMS M&O 2000ek).

Several supplemental analyses related to the saturated zone have been conducted since the TSPA-SR model was completed. The first supplemental analysis is part of the effort made by the DOE to improve the treatment of uncertainty in current models (Section 4.1.1.2) and concerns several changes made to refine the uncertainty in the saturated zone flow and transport model. The remaining analyses are sensitivity studies that examine specific parameter values. The second and third new analyses look at the question of how the results of the TSPA-SR model would change if there was no matrix diffusion and if there was more matrix diffusion in the volcanic rocks in the saturated zone. The fourth analysis looks at how the TSPA-SR results would change if the flow paths in the saturated zone encountered minimum alluvium in the southern half of the model domain. The fifth analysis looks at how the results would change if greater uncertainty is included in the parameters for the two models describing colloid-facilitated transport.

Unquantified Uncertainty in the Saturated Zone—The saturated zone flow and transport model was modified to include new information and in response to the effort to evaluate unquantified uncertainty in the TSPA-SR model. These modifications have been based on insights from the uncertainty analyses (BSC 2001a, Section 12.3; BSC 2001b, Section 3.2.10.2) and to include new data (BSC 2001a, Section 12.3.2.2) developed since the completion of the TSPA-SR model. A more realistic representation of the bulk density of the alluvium is included based on new borehole gravimeter data (BSC 2001a, Section 12.3.2.4). Continuing data collection from batch and column sorption experiments for iodine-129 and technetium-99 with alluvium samples indicates that the sorption coefficients for these radionuclides are zero under oxidizing conditions (BSC 2001a, Section 12.3.2.2). A more detailed discussion is contained in Volume 1, Section 12.5.1 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a). Changes that are most significant to

TSPA dose calculations include the following (BSC 2001b, Section 3.2.10.2.1):

- Bulk density of the alluvium, a factor in determining the amount of sorption that a radionuclide undergoes, was changed from a constant (1.27 g/cm^3) to a variable (normal distribution with a mean of 1.91 g/cm^3 and standard deviation of 0.08 g/cm^3).

- The sorption coefficients in the alluvium for technetium and iodine were set to zero; they were previously represented with uncertainty distributions with very low values.

- The sorption-coefficient distribution for neptunium was assigned to somewhat lower values: the sorption-coefficient distribution of uranium is made equal to that of neptunium, and the two distributions were correlated in the alluvium.

- The diffusion coefficient was changed from a log-uniform distribution to a log-triangular distribution with the same range but with a mode of 3.2×10^{-11} m^2/s.

- The amount of uncertainty in the saturated zone flux was reduced. For the TSPA-SR model, three saturated zone fluxes were considered: high, medium, and low. Each differed by a factor of 10: 6, 0.6, and 0.06 m/yr (20, 2, and 0.2 ft/yr), respectively, in the vicinity of the repository. For the analysis of unquantified uncertainties, the high, medium, and low fluxes differed by a factor of 3: 1.8, 0.6, and 0.2 m/yr (6, 2, and 0.7 ft/yr).

There is virtually no difference between the mean annual doses calculated by the TSPA-SR model and by the supplemental saturated zone model incorporating these changes (BSC 2001b, Section 3.2.10.2, Figure 3.2.10-1(a)). From a total-system perspective, the overall effect of changes made for the analysis of unquantified uncertainties tend to counteract each other.

No Matrix Diffusion in the Saturated Zone—For the purposes of this sensitivity study, the diffusion coefficient is reduced by 10 orders of magnitude. A more detailed discussion of the changes made to the saturated zone modeling is contained in Volume 1, Section 12.5.2.1 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a).

The differences between results of the TSPA-SR model with matrix diffusion and the model without are slight (BSC 2001b, Section 3.2.10.2.2). The most likely reason for this is that approximately half of the TSPA-SR realizations have little or no matrix diffusion because of a low diffusion coefficient, large flowing interval spacing, or a high groundwater flux. The mean annual dose is primarily influenced by the realizations that produce the high annual dose values, particularly for neptunium-237. On average, approximately a fourth of the high-dose realizations include a saturated zone that has little or no matrix diffusion. Reducing matrix diffusion in the other half of the realizations that have matrix diffusion does little to increase the mean annual dose (BSC 2001b, Section 3.2.10.2.2).

Enhanced Matrix Diffusion in the Saturated Zone—To create an enhanced matrix diffusion model, the flowing interval spacing in the saturated zone site-scale flow and transport model is reduced; in particular the mean of the distribution was reduced by a factor of 100. A more detailed discussion of the changes made to the saturated zone modeling is contained in Volume 1, Section 12.5.2.2 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a).

The differences between the results of the TSPA-SR model and the model with enhanced matrix diffusion are generally less than 20 percent, and the simulated doses are somewhat lower for the model with enhanced matrix diffusion, as expected (BSC 2001b, Section 3.2.10.2.3, Figure 3.2.10-3(a)). The mean annual dose in the TSPA-SR model is primarily influenced by the realizations that produce the high annual dose values, particularly for neptunium-237. The sorption coefficient for neptunium in the volcanic matrix averages 0.5 ml/g; thus, even if neptunium does diffuse into the matrix, there is little retardation. The modeled combination of high groundwater fluxes, low diffusion coefficient, and low neptunium sorption coefficient tends mostly to override the effect of a reduced flowing interval spacing, at least in the mean annual dose (BSC 2001b, Section 3.2.10.2.3).

Minimum Flow Path Length in the Alluvium—The alluvial uncertainty zone is a region in the TSPA-SR saturated zone site-scale model (CRWMS M&O 2000a, Section 3.8.2.4; CRWMS M&O 2000bn, Section 3.7.2) that encompasses the area where flow paths from a repository at Yucca Mountain might enter alluvial deposits in southern Jackass Flats. The alluvial uncertainty zone is approximately 5 km (3 mi) wide by 8 km (5 mi) long (in the north–south direction). In this sensitivity study, the length of the alluvial uncertainty zone is set to zero in the saturated zone model. There is still approximately 1 km (0.6 mi) of alluvium at the 20-km (12-mi) boundary used in the model. As discussed in Volume 2, Section 3.2.10.2.4 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b), the results from the sensitivity analysis differ only slightly (generally less than 10 percent) from TSPA-SR model results.

Increased Uncertainty in the Colloid-Facilitated Transport Models—For TSPA-SR, the colloid concentrations for both irreversible colloids and reversible colloids were calculated from functions of ionic strength that included no uncertainty. The sensitivity study defined here is for a new colloid-facilitated transport model as discussed in Volume 1, Sections 9.3.4 and 10.3.5 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a), which includes probability distributions for colloid concentrations and an expanded probability distribution for the sorption coefficient for radionuclides onto colloids.

For irreversible colloids, a mass flux of plutonium and americium associated with these colloids is introduced to the saturated zone at the unsaturated zone-saturated zone interface and their transport is tracked. In the volcanic units, these colloids are restricted to the fractures where they undergo transport and retardation as in the TSPA-SR model. In the alluvium, a new distribution of the retardation factor for radionuclides irreversibly sorbed onto colloids is used in this sensitivity study. The distribution results in lower retardation factors than the retardation distribution used in the TSPA-SR model (BSC 2001a, Section 12.3.2.4.5.2). For reversible colloids, a mass flux of radionuclides associated with these colloids is also tracked from the unsaturated zone–saturated zone interface (BSC 2001a, Section 12.5.2.4; BSC 2001b, Section 3.2.10.2.5).

There is virtually no difference in the mean annual dose using the supplemental colloid model compared with the colloid model used in the TSPA-SR analyses (BSC 2001b, Section 3.2.10.2.5, Figure 3.2.10-5). The two radionuclides that comprise greater than 70 percent of the annual dose in the TSPA-SR model are technetium at earlier times and neptunium at later times. Both of these radionuclides are transported as solute and thus are unaffected by the new colloid model. Also, in the new colloid model the means of the distributions (for colloid concentrations, sorption coefficients for radionuclides onto colloids, and sorption coefficients for radionuclides onto the rock matrix and alluvium) are similar to values used in TSPA-SR, and thus the mean behavior was not expected to be significantly different.

4.2.9.3.2 Alternative Conceptual Processes

Luckey et al. (1996, p. 52) reviewed the major conceptual uncertainties relating to the saturated zone flow system at Yucca Mountain. They identified the following major areas of uncertainty:

- Whether the flow system can be simulated as a porous medium or if discrete features need to be simulated
- Behavior of the flow system in the areas of the large hydraulic gradient and the moderate hydraulic gradient
- Recharge and the time-scale at which it comes into equilibrium with climate
- How best to translate data from field sampling and borehole testing to the scale of the flow models.

Numerical modeling of fracture properties is done in one of two ways: discrete fracture models or effective continuum models. Discrete fracture models represent each fracture as a distinct object within the modeling domain. The effective continuum representation of fracture permeability is used for the site-scale saturated zone flow and transport model for the following reasons (CRWMS M&O 2000bn, Section 3.5.1):

- The exact characterization of hydraulic and geometric properties of fractures necessary to construct an accurate discrete fracture model does not exist for Yucca Mountain.

- At Yucca Mountain, studies of the density and spacing of flowing intervals generally indicate that flow occurs through fracture zones (CRWMS M&O 2000em, Figure 15).

- Part of the flow system is an alluvium unit for which flow and transport is appropriately modeled using a continuum model.

- The drawdown response (drop in water level) to pumping at wells surrounding the C-Wells Complex in multiwell pump tests indicates a well-connected fracture network in the Miocene tuffaceous rocks in this area (Geldon, Umari, Earle et al. 1998, p. 31).

- Although the discrete fracture approach retains the discrete nature of the observed fractures within the model, the computational burden of calculating a flow solution using a discrete fracture model becomes extremely large even for relatively simple fracture models.

Whether the flow system can be simulated as an effective continuum model is addressed in *Calibration of the Site-Scale Saturated Zone Flow Model* (CRWMS M&O 2000ej, Section 6.1.1), which notes that the site-scale saturated zone flow and transport model uses the effective continuum representation of fracture permeability.

Although the site-scale saturated zone flow and transport model is a continuum model, special hydrologic features, including selected major faults, fault zones, and zones of chemical alteration, are treated in the model as zones of enhanced or reduced permeability (CRWMS M&O 2000ej, Table 6). Because the major faults and fault zones are represented directly in the model and because of the scale of use of the model, no impact results from using a continuum model over a discrete fractures model.

Luckey et al. (1996) present detailed descriptions of the gradient features and discuss interpretations of their causes (CRWMS M&O 2000bn, Section 3.2.2.3). The large hydraulic gradient, particularly, has been the subject of numerous theories. Current models assume that the hydraulic gradient is caused by semi-perched water. This assumption is based on the formal expert elicitation and recent test results discussed next.

An expert elicitation panel on saturated zone flow and transport, which was convened by the DOE, addressed the cause of the large hydraulic gradient (CRWMS M&O 1998j, pp. 3-5 to 3-6). The panel narrowed the theories to the two most credible hypotheses: the large hydraulic gradient is caused by flow through the upper volcanic confining unit or it is a result of semi-perched water. The consensus of the panel slightly favored semi-perched water. The experts were in agreement that the issue was mainly one of technical credibility, that the probability of any large transient change in the configuration of the large gradient is low, and that long-term transient readjustment of gradients was of low probability (CRWMS M&O 1998j, p. 4-3).

The only important new results pertaining to the cause of the large gradient include the drilling of borehole WT-24 in the area of the large gradient and the analysis of hydrochemical data in *Geochemical and Isotopic Constraints on Ground-Water Flow Directions, Mixing, and Recharge at Yucca Mountain, Nevada* (CRWMS M&O 2000eg, Section 6.4.2). The drilling of borehole WT-24 supported the previous portrayal that the large gradient (Tucci and Burkhardt 1995, Figure 4) probably included perched water; however, the question of whether perching of water is the cause of the large gradient was not fully resolved.

Hydrochemical information on the ratio of uranium-234 to uranium-238 presented in

Geochemical and Isotopic Constraints on Ground-Water Flow Directions, Mixing, and Recharge at Yucca Mountain, Nevada (CRWMS M&O 2000eg, Section 6.5.3) suggests that local recharge, as represented by perched water, is a major component in the groundwater at Yucca Mountain.

Perched water was encountered in seven boreholes near the potential repository (CRWMS M&O 2000b, Section 8.5.2). The contact zone between the Topopah Spring welded and the Calico Hills nonwelded hydrogeologic units is characterized by a basal vitrophyre stratum in the Topopah Spring welded hydrogeologic unit above a zone of zeolitic altered tuffs in the Calico Hills nonwelded hydrogeologic unit. For a perched zone to exist, the vertical permeability of the perching units would have to be low (less than 1 microdarcy) and fracture permeability would have to be negligible.

Horizontal Anisotropy—Anisotropic conditions exist if the permeability of media varies as a function of direction. Because groundwater primarily flows in fractures within the volcanic units downgradient of Yucca Mountain and because fractures and faults occur in preferred orientations, it is possible that anisotropic conditions of horizontal permeability exist along the pathway of potential radionuclide migration in the saturated zone (CRWMS M&O 2000bn, Section 3.2.5.3). Performance of the potential repository could be affected by horizontal anisotropy because the flow could be diverted to the south, causing transported solutes to remain in the fractured volcanic tuff for longer distances before moving into the valley fill alluvial aquifer. A reduction in the length of the flow path in the alluvium would decrease the amount of radionuclide retardation that could occur for those radionuclides with greater sorption coefficients in alluvium than in fractured volcanic rock matrix. In addition, potentially limited matrix diffusion in the fractured volcanic units could lead to shorter transport in the volcanic units relative to the alluvium.

A conceptual model of horizontal anisotropy in the tuff aquifer is reasonable, given that flow in the tuff aquifer is believed to occur in a fracture network that exhibits a preferential north–south strike azimuth (CRWMS M&O 2000en, Section 5.5). Major faults near Yucca Mountain that have been mapped at the surface also have a similar preferential orientation (Figure 4-144). In addition, north to north-northeast striking structural features are optimally oriented perpendicular to the direction of least principal horizontal compressive stress thus promoting flow in that direction, suggesting a tendency toward dilation and potentially higher permeability (Ferrill et al. 1999, pp. 5 to 6).

Evaluation of the long-term pumping tests at the C-Wells Complex supports the conclusion that large-scale horizontal anisotropy of aquifer permeability may occur in the saturated zone (Ferrill et al. 1999, p. 7). Results of this hydrologic evaluation generally are consistent with the structural analysis of potential anisotropy. However, there are important uncertainties, including differences in pumping test analysis methods; the fact that only a minimum number of observation wells were used; and the additional uncertainty regarding the validity of assuming a homogenous effective continuum over the scale of the test (Winterle and La Femina 1999, p. 4-29).

Taken together, these observations and inferences support an alternative conceptual model (Figure 4-145) in which large-scale horizontal anisotropy of permeability, with higher permeability in a north-northeasterly direction, occurs in the volcanic units of the saturated zone to the southeast of the potential repository. Because of existing uncertainty in the interpretation of the large-scale horizontal anisotropy in permeability, the simpler, horizontal isotropic model of permeability was retained as the nominal conceptual model. The large-scale horizontal anisotropy in permeability is considered an alternative plausible model. To evaluate the uncertainty in anisotropy (isotropy/anisotropy), two discrete cases were examined. These consist of two alternative models: the isotropic case and the anisotropic case with a 5 to 1 anisotropy ratio. To evaluate the uncertainty in groundwater flux, three discrete cases were examined. These consist of the mean case (corresponding to the mean flux of the calibrated site-scale saturated zone flow model), the low case (mean flux time 0.1), and the high case (mean flux time 10). The flux multiplier and the corresponding probabilities for these cases are quantified based on the uncertainty distribution for discharge in the

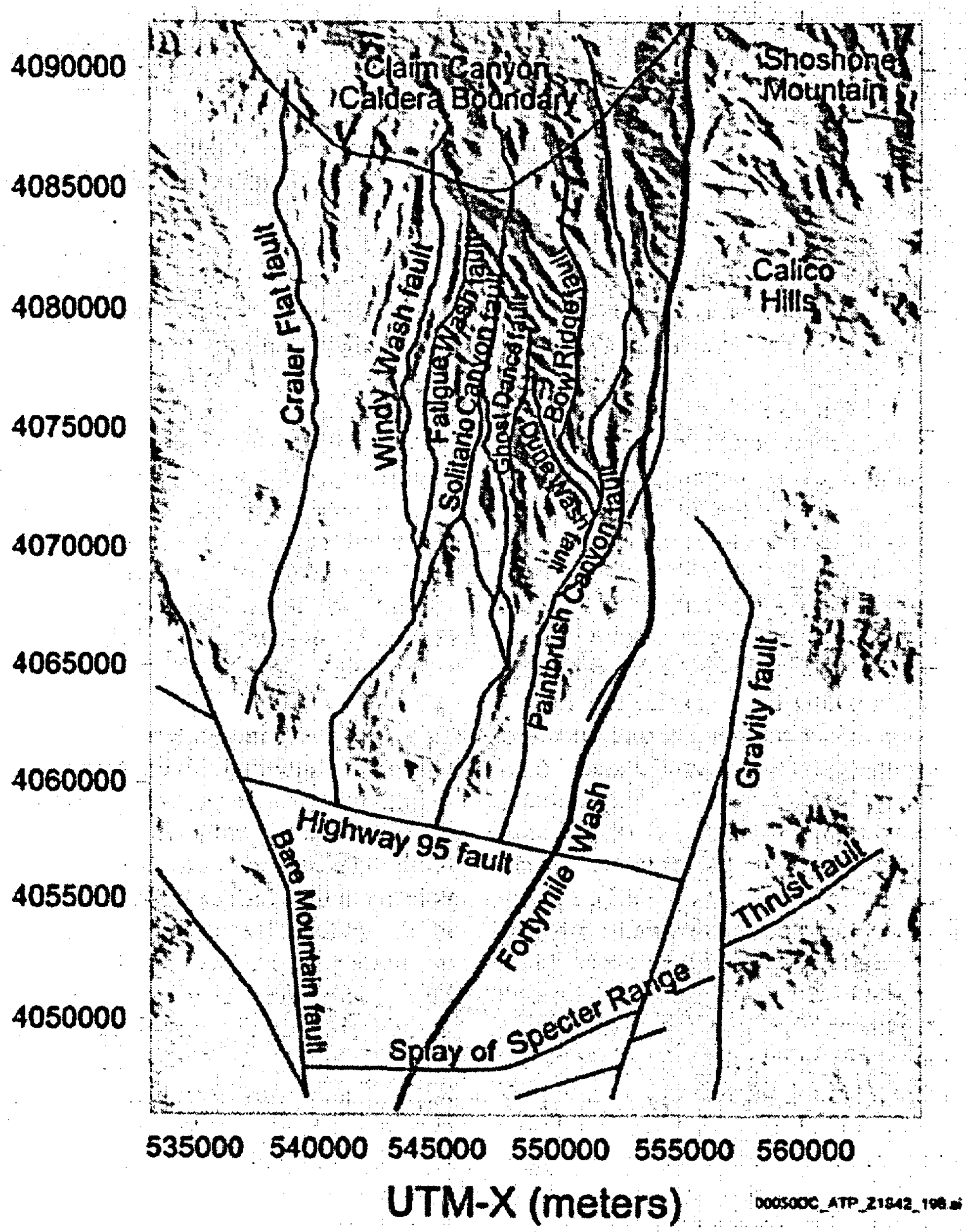


Figure 4-144. Structural and Tectonic Features within the Site-Scale Saturated Zone Model
Large known features are implicitly represented in the site-scale flow and transport model. UTM = Universal Transverse Mercator. Source: CRWMS M&O 2000bn, Figure 3-4.

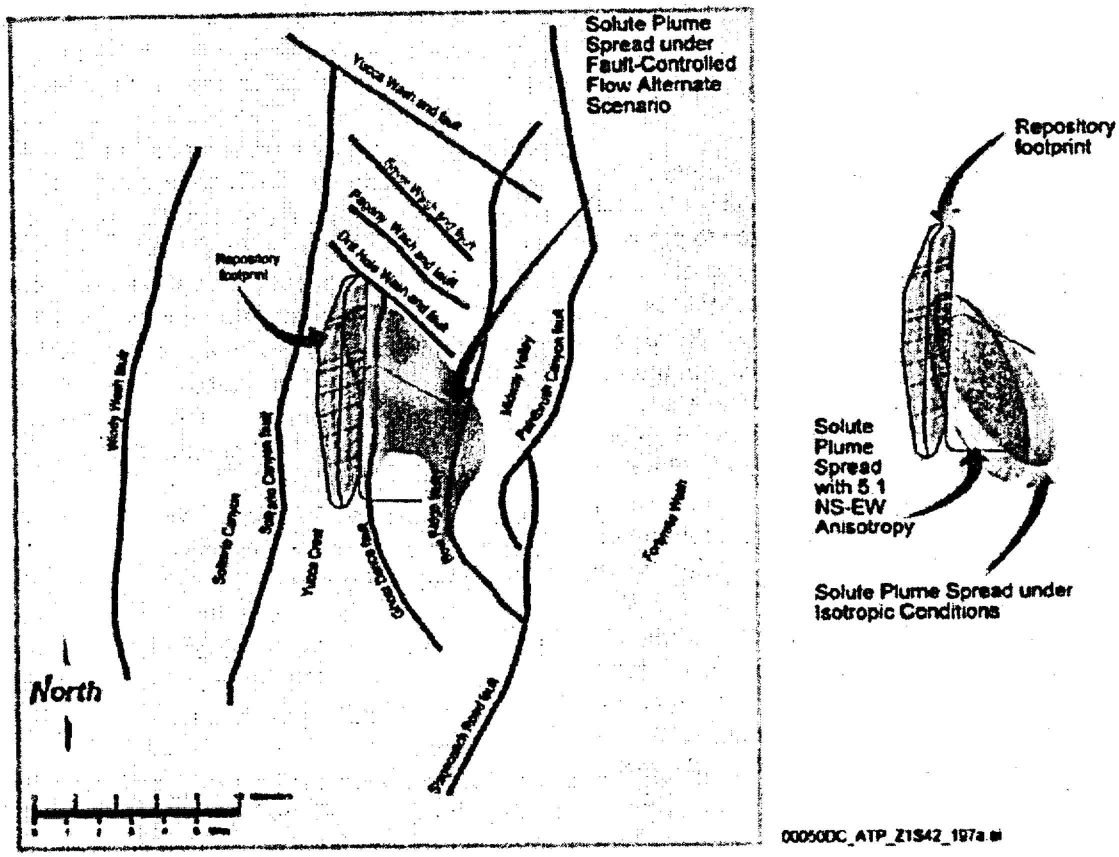


Figure 4-145. The Use of Anisotropy to Simulate an Alternate Conceptual Flow and Transport Model
In this case it is assumed that observed faults to the south and east of Yucca Mountain tend to divert flow to the south. The north–south hydraulic conductivity in the upper layers of the porous medium flow model were increased by a factor of five to increase the southerly flow and simulate the effect of the faults. The solute plumes in the right panel conceptually illustrate the effect of faults on transport and the effect of the introduction of anisotropy in the porous media flow model on transport in the mathematical model.

volcanic aquifer from the saturated zone expert elicitation (CRWMS M&O 1998j, Section 3.2.3). The analysis is provided in *Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA* (CRWMS M&O 2000el, Section 6.2.5). The results of considering both types of uncertainty are six alternative groundwater flow fields (three flux cases times two anisotropy cases).

Implementation of the alternative groundwater flow fields is accomplished by establishing a steady-state solution of groundwater flow in the site-scale saturated zone model for each of the six cases. Small variations in the simulated heads (i.e., hydraulic pressure) exist among the six steady-state flow solutions (generally variations of less than 1 m [3.3 ft]). All six flow fields represent acceptable matches to measured water levels. The steady-state conditions for each of these cases are imposed as the initial conditions for TSPA simulations of radionuclide transport. In addition, a separate set of input files for the site-scale saturated zone flow and transport model that incorporate modifications to the boundary conditions and value of permeability for each case are constructed. Each simulation is assigned to the appropriate flow field based on the values of the stochastic parameters that represent uncertainty in flux and horizontal anisotropy.

4.2.9.3.3 Saturated Zone Flow and Transport Model Calibration and Validation

4.2.9.3.3.1 Flow Model Calibration

Calibration, also known as inverse modeling, is the process by which values of important model parameters are estimated and optimized to produce the best fit of the model output to the observed data. Calibration is generally accomplished by varying model parameters to minimize the difference between observed and simulated conditions. The site-scale saturated zone flow and transport model was calibrated largely by automated procedures, but manual adjustments to the calibration were also performed to ensure an accurate and conservative model. During the calibration process, nodal values of permeability were adjusted to minimize the differences between observed and simulated values of water levels and groundwater fluxes along the northern and eastern boundaries of the model domain. One hundred fifteen water level and head measurements were used as calibration targets (CRWMS M&O 2000bn, Section 3.3.6).

During the calibration process, special emphasis or weighting was given to minimizing the difference between observed and simulated water levels at selected locations. Preferential weighting was applied to approximately thirty calibration targets in the low-gradient region to the south and east of Yucca Mountain. These calibration targets were given high weighting because they are in the likely pathway of fluid leaving the potential repository site and because small changes in head in this area could produce a large effect on the flow direction. The single head measurement in the carbonate aquifer was also given preferential weighting because of the importance of this calibration target for reproducing an upward gradient in the calibrated model. The inclusion of an upward gradient within the calibrated site-scale saturated zone flow and transport model is considered important for generating a realistic model. Calibration targets north of Yucca Mountain were given low weighting, primarily because of the possibility of perching and the attendant uncertainty in water-level measurements in this region.

During calibration, sets of nodes were grouped into specific permeability zones based on similar permeability characteristics, and a single permeability variable was assigned to each zone. These values of zonal permeability variables served as the parameters that were optimized during model calibration. Permeability zones were created for each of the hydrogeologic units identified in the hydrogeologic framework model and for specific hydrogeologic features. All of the nodes within a specific hydrogeologic unit were assigned to that permeability zone unless they were included in one of the permeability zones established for specific hydrogeologic features. The hydrogeologic features for which special permeability zones were established were primarily faults, fault zones, and areas of chemical alteration. Twenty-seven permeability zones were established for model calibration, and permeability values or multipliers were assigned to each zone. Upper and lower bounds were placed on each permeability variable during calibration. The upper and lower bounds for the permeabilities and permeability multipliers were chosen to reflect maximum and minimum field values (permeability) or a realistic range of values (permeability multipliers). Horizontal isotropy in permeability was assumed at all nodes.

4.2.9.3.3.2 Calibration Results

A potentiometric surface was generated using the calibrated site-scale saturated zone flow and transport model, and residual heads remaining after calibration were computed by subtracting the observed head from the predicted head (Figure 4-146). The largest head residuals (about 100 m [330 ft]) are in the northern part of the model (in the high-head gradient area). These head residuals are largely the result of the low weighting assigned to these calibration targets and of the uncertainty in these measurements due to the perched conditions that may exist in this area. The next highest group of head residuals border the east–west barrier and Solitario Canyon fault. These residuals likely result from a grid resolution insufficient to resolve the 780- to 730-m (2,560- to 2,400-ft) drop in head that occurs over a short distance in this area. Head residuals in the low-gradient area along the expected migration pathway away from the poten-

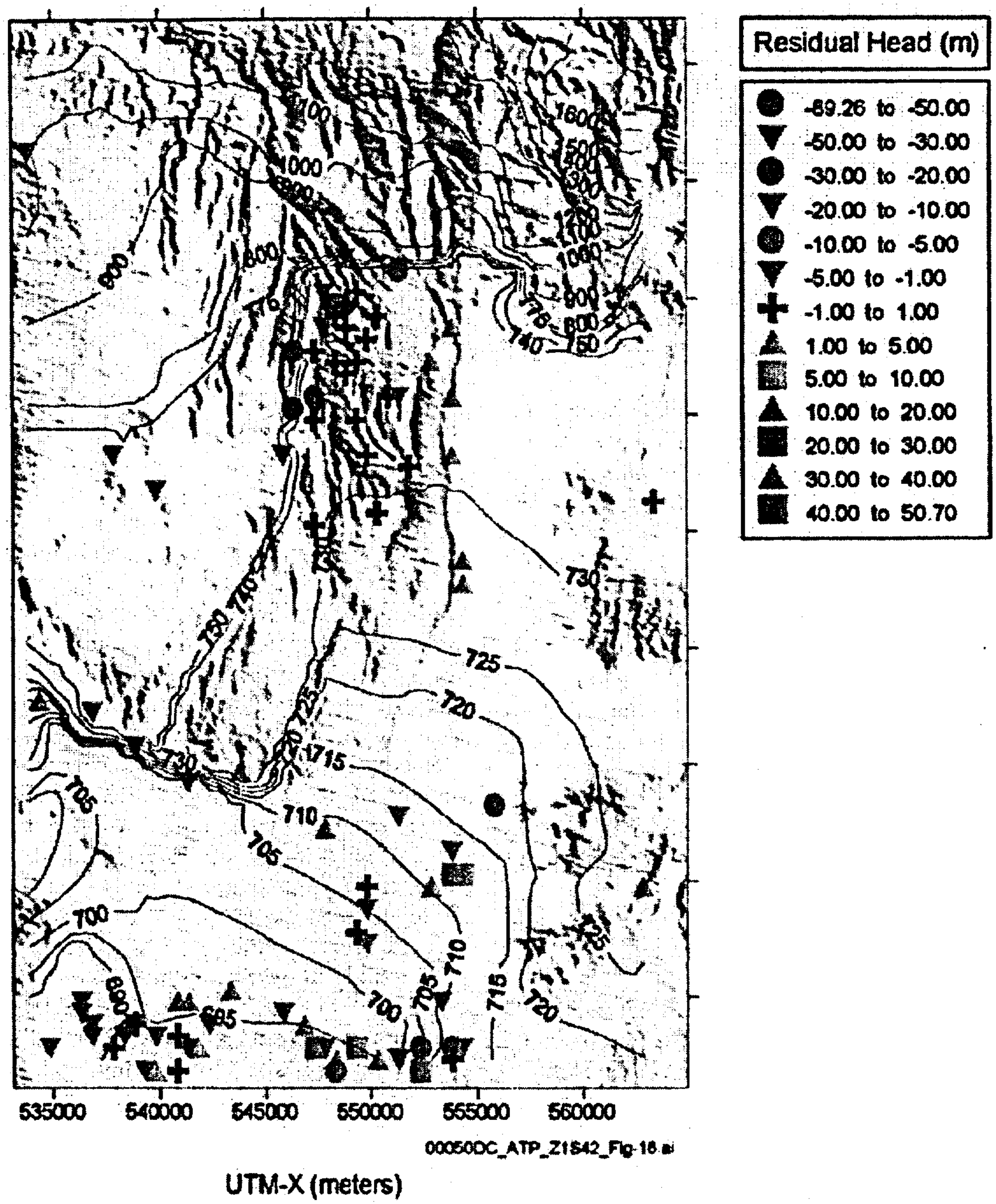


Figure 4-146. Simulated Potentiometric Surface with Three-Dimensional Flow Model Calibration Residuals
The calibration residual is computed by taking the difference between the observed hydraulic head and the predicted hydraulic head. This calibration supported the TSPA-SR. UTM = Universal Transverse Mercator. Source: CRWMS M&O 2000bn, Figure 3-20.

tial repository are generally low (CRWMS M&O 2000bn, Section 3.3.7).

The particle-tracking capability of FEHM was used to demonstrate the predicted flow paths from the potential repository (Figure 4-147). The predicted pathways generally leave the potential repository and lead in a south-southeasterly direction to the accessible environment. From the accessible environment to the end of the model domain (approximately the 30-km [19-mi] boundary), the flow paths trend to the south-southwest and generally follow Fortymile Wash.

The calibrated flow model was used to estimate the specific discharge for a nominal fluid path leaving the potential repository area and traveling to 5, 20, and 30 km (approximately 3.1, 12, and 19 mi). For these three points, values for specific discharge of 0.6 m/yr, 2.3 m/yr, and 2.7 m/yr (2.0, 7.5, and 8.9 ft/yr), respectively, were obtained. An expert elicitation panel estimated a specific discharge of 0.71 m/yr (2.3 ft/yr) for the volcanic aquifer at 5 km (3.1 mi) (CRWMS M&O 1998j, Figure 3-2e). Thus, agreement between the specific discharge predicted by the calibrated model and that estimated by the expert elicitation panel for 5 km (3.1 mi) is good, and the value predicted by the calibrated model is conservative. The expert elicitation committee did not consider other boundaries.

4.2.9.3.3.3 Flow Model Validation

Model validation is the process of testing the validity of the conceptualization of the processes represented in the model and testing the validity of the mathematical representation and numerical implementation. The results of the calibrated site-scale saturated zone flow and transport model have undergone analyses to validate the model (CRWMS M&O 2000bn, Section 3.4). These analyses include a comparison of the calibrated permeability values with observed permeability data, a comparison between boundary fluxes predicted by the regional-scale flow model and the calibrated site-scale saturated zone flow and transport model, a comparison between the observed and predicted gradients between the carbonate aquifer and overlying volcanic aquifers, and a comparison between hydrochemical data and particle pathways predicted by the model.

Permeability—For model validation, the permeabilities estimated during calibration of the site-scale saturated zone flow and transport model were compared to permeabilities determined from aquifer test data from the Yucca Mountain area and elsewhere at the Nevada Test Site (CRWMS M&O 2000bn, Section 3.4.1). Data from reports pertaining to the Nevada Test Site were included in the comparison to help constrain permeability estimates for hydrogeologic units that were not tested or that underwent minimal testing at Yucca Mountain. The logarithms of permeability estimated during calibration of the model were compared to the mean logarithms of permeability determined from aquifer test data from Yucca Mountain (Figure 4-148) and to data from elsewhere at the Nevada Test Site (Figure 4-149). For most of the geologic units, the calibrated permeabilities were within the 95 percent confidence limits of the mean permeabilities estimated from the data (Figure 4-148). The model-calibrated permeability value for the carbonate aquifer is well within the 95 percent confidence interval for the mean permeability of the carbonate aquifer beneath Yucca Mountain, which has been estimated from field testing (Figure 4-148). However, both of these permeability values are about an order of magnitude less than the estimated mean permeability of the carbonate aquifer derived from aquifer tests performed elsewhere on the Nevada Test Site (Figure 4-149). Given these available data, the agreement between the model-calibrated value and the estimated site permeability value for the carbonate aquifer is considered to provide an adequate basis for confidence in the validity and representativeness of the site-scale flow model. Figure 4-149 also suggests a discrepancy between the model-calibrated permeability value for the upper volcanic aquifer and the estimated mean value obtained from field testing elsewhere on the Nevada Test Site. The field test permeability data, however, have been inferred from only two transmissivity values estimated from drawdown curves in two boreholes and are insufficient to either yield reliable permeability values or estimate confidence intervals for these data (CRWMS M&O 2000ej,

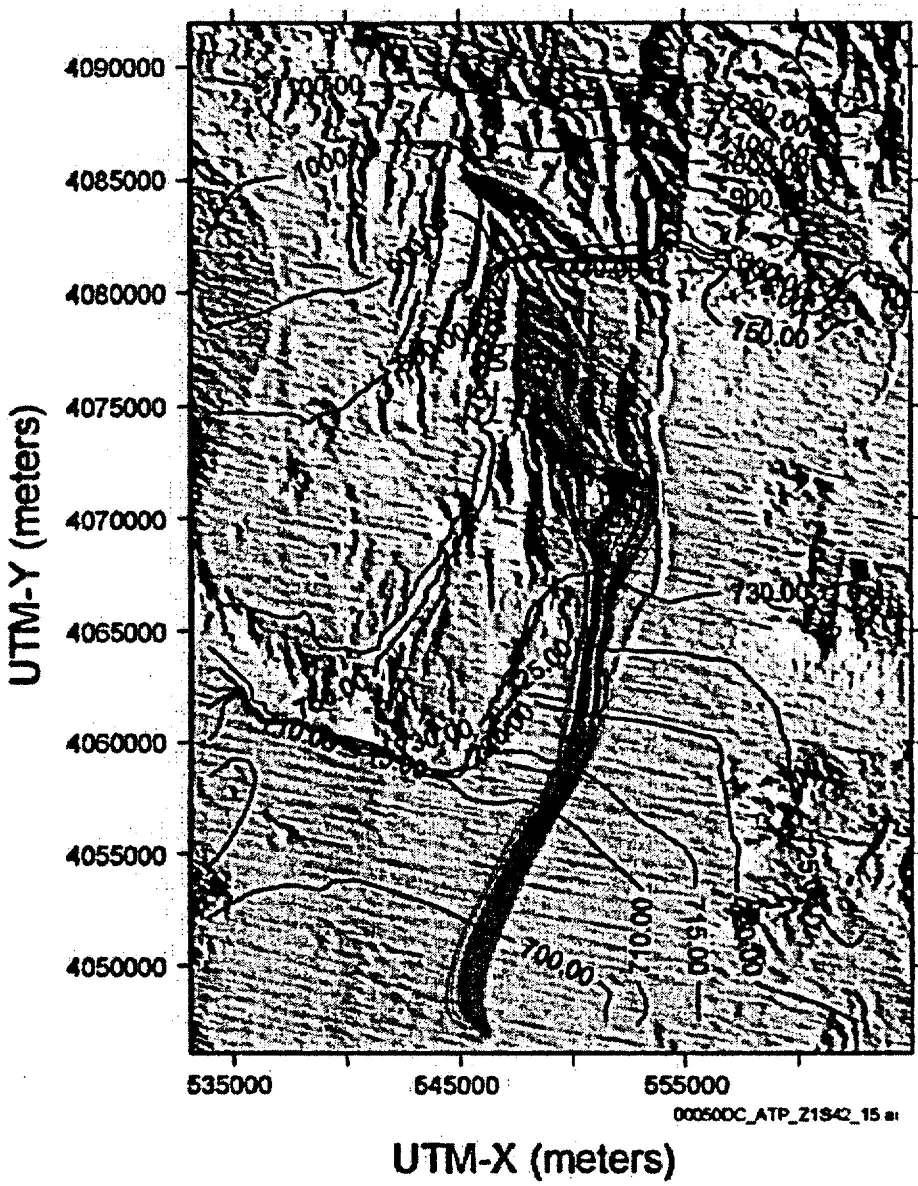


Figure 4-147. Simulated Particle Paths after a Hypothetical Radionuclide Release from the Potential Repository

The particle paths were superimposed on a shaded relief map of the surface topography. The particles were distributed in the repository footprint in the saturated zone. This analysis supported the TSPA-SR. UTM = Universal Transverse Mercator. Source: CRWMS M&O 2000bn, Figure 3-21.

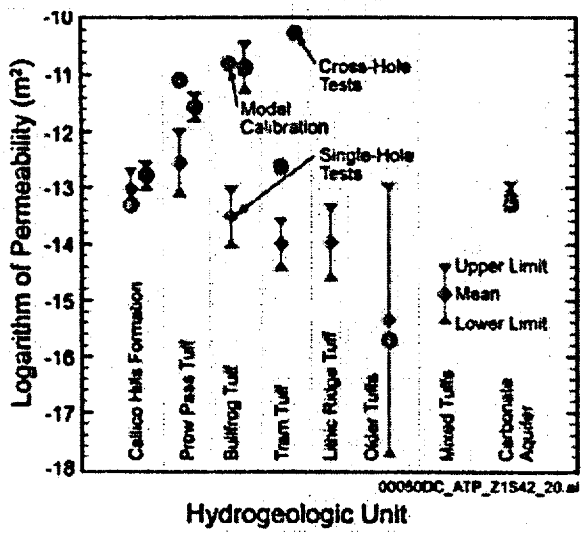


Figure 4-148. Estimated and Observed Permeabilities for Nine Stratigraphic Units at Yucca Mountain

Estimated permeabilities calculated from the site-scale saturated zone flow and transport model. Observed permeabilities calculated from pump-test data. Bars indicate 95 percent confidence intervals; diamonds indicate the mean value. Source: CRWMS M&O 2000bn, Figure 3-22.

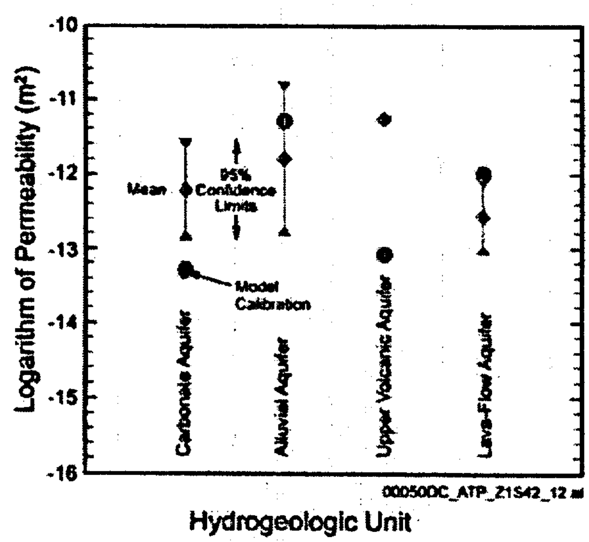


Figure 4-149. Estimated and Observed Permeabilities for Four Aquifers at Yucca Mountain

Estimated permeabilities calculated from the site-scale saturated zone flow and transport model. Observed permeabilities calculated from pump-test data. Bars indicate 95 percent confidence intervals; diamonds indicate the mean value. Source: CRWMS M&O 2000bn, Figure 3-23.

Section 6.7.7.6). Because the upper volcanic aquifer is expected to contribute little to potential radionuclide transport through the saturated zone (CRWMS M&O 2000ej, Figure 17), the model-calibrated permeability value for this unit is considered to be adequate for the intended application of the model.

With the exception of the calibrated values for the upper volcanic aquifer, the calibrated permeabilities generally are consistent with most of the permeability data from Yucca Mountain and elsewhere at the Nevada Test Site. A discrepancy exists between the calibrated permeability for the Tram Tuff of the Crater Flat Group and the mean permeability derived from the cross-hole tests. However, the permeabilities measured for the Tram Tuff of the Crater Flat Group may have been enhanced by the presence of a breccia zone in the unit at boreholes UE-25 c#2 and UE-25 c#3 (Geldon, Umari, Fahy et al. 1997, Figure 3).

Boundary Fluxes—A comparison of the fluxes predicted at the boundary of the site-scale model domain by the calibrated site-scale saturated zone flow and transport model and by the regional-scale model was used to further validate the model (CRWMS M&O 2000bn, Section 3.4.2). The mass fluxes computed along the boundaries by the two models match reasonably well. The total fluxes across the northern boundary computed by the regional-scale model and the site-scale saturated zone flow and transport model were 189 kg/s and 169 kg/s (416 lbs/s and 372 lbs/s), respectively, a difference of 11 percent. The fluxes computed for individual segments along the northern boundary by the two models are distributed somewhat differently. However, this difference in distribution can be expected because the regional-scale and site-scale models are based on different hydrogeologic framework models. The comparison of the boundary fluxes computed along the east side of the site-scale saturated zone flow model domain also indicates a good match. The total fluxes across the eastern boundary computed by the regional-scale model and the site-scale model were 561 kg/s (1,236 lb/s) and 517 kg/s (1,139 lbs/s), respectively. The match is particularly good along the lower thrust area, where both models predict large fluxes across the model boundary. Both models also predicted small fluxes across the remainder of the eastern boundary.

The fluxes across the western boundary computed by the regional-scale model and the site-scale model do not match as well as along the northern and eastern boundaries. The regional-scale model predicts greater inflow along the western boundary than does the site-scale model. The discrepancy in fluxes computed along the western boundary by the two models is largely the result of the different hydrogeologic framework models upon which the two models are based. For example, the newer hydrogeologic framework model used as the basis for the site-scale model includes a large amount of low permeability clastic rock along the southernmost portion of the western boundary that was not included in the regional-scale model. This zone of low-permeability rock would not support the large flux predicted by the regional-scale model across this portion of the western boundary. For these reasons, it is concluded that the site-scale model estimated flux is appropriate.

The southern boundary flux is simply a sum of the other boundary fluxes plus the recharge. A comparison of the fluxes across the southern boundary computed by the regional-scale model and the site-scale saturated zone flow and transport model indicates a relatively good match. The difference in the fluxes computed by the two models across the southern boundary is approximately 21 percent.

Upward Hydraulic Gradient—An upward hydraulic gradient between the lower carbonate aquifer and the overlying volcanic rocks has been observed in the vicinity of Yucca Mountain. Principal evidence for this upward gradient is provided by data from the only borehole at Yucca Mountain that has been drilled into the upper part of the carbonate aquifer. Hydraulic head measurements in this borehole indicate that the head in the carbonate aquifer is about 752 m (2,470 ft), about 22 m (72 ft) higher than the head measured in this borehole in the overlying volcanic rocks. Although the head in the carbonate aquifer at this borehole location was not held fixed, but was estimated as part of the model calibration process, increasing head with depth at this location (but not the precise magnitude of the observed hydraulic gradient) was preserved during model calibration. As indicated by geochemical data, preserving the sense of the upward gradient is important to ensure that the modeled flow paths in the carbonate aquifer remain shallow and confined within the upper part of the aquifer. The difference in predicted and observed values of the upward hydraulic gradient at this location results, in part, because the constant vertical head boundary conditions imposed on the lateral boundaries of the model domain restricted the accurate representation of vertical groundwater flow and gradients within the model interior (CRWMS M&O 2000ej, Sections 6.7.11 and 6.1.2).

The failure to fully represent the entire magnitude of this upward vertical gradient can be attributed, in part, to the constant-head conditions established at the boundaries of the model (the same value of the constant-head boundary was specified for all layers (i.e., the same with depth)). The constant-head conditions applied to each layer of the model at each boundary did not allow vertical flow at the boundaries. However, vertical gradients developed within the model domain in response to geohydrologic conditions. Although the upward gradient produced by the model is not as large as that indicated by field measurements, it nevertheless is sufficient to keep the simulated fluid path lines downgradient from the potential repository in the shallow volcanic aquifers.

Hydrochemical Data Trends—To provide further validation of the site-scale saturated zone flow and transport model, the flow paths (Figure 4-147) predicted by the calibrated model were compared with those estimated using groundwater chemical and isotopic data (Figure 4-133) (CRWMS M&O 2000bn, Section 3.4.4). Flow paths predicted by the calibrated site-scale saturated zone flow model were generated using the particle-tracking capability of the FEHM code by placing particles at various depths along the western, northern, and eastern boundaries and running the model to trace the paths of these particles for 1 million years.

Comparison of the flow paths predicted by the calibrated model with those estimated using groundwater chemical and isotopic data indicate that some differences exist between the flow directions determined by the two approaches. The most prominent difference is the stronger eastward component of flow in the Crater Flat area predicted by the numerical model as compared to flow directions determined with the hydrochemical data. The differences in flow directions estimated for Crater Flat could be due to the inability of the simple hydrochemical analysis to account for vertical mixing due to recharge or mixing between aquifers, the assumption in the numerical model that the permeability of subsurface material in Crater Flat is isotropic, or a combination of these factors. However, the important flow paths leading away from the potential repository area are similar for both methods.

Saturated Zone Transport Model—To test conceptual models of saturated zone transport in fractured tuffs, the DOE conducted several cross-hole tracer and hydraulic tests at the C-Wells Complex between 1995 and 1999 (CRWMS M&O 2000eb, Section 6.9). The discussion here focuses on two tracer tests involving the injection of multiple tracers, as these tests provided the most rigorous and convincing testing of conceptual transport model for saturated, fractured tuffs (Figure 4-150). One of these tests was conducted in the lower Bullfrog Tuff, the most transmissive interval at the C-Wells, and the other was conducted in the lower Prow Pass Tuff, which had relatively low transmissivity. Additional information on the field testing and the parallel laboratory studies is presented in *Saturated Zone Flow and Transport Process Model Report* (CRWMS M&O 2000bn, Section 3.1.3.2.1).

The principal conclusions from the C-Wells field and laboratory tests relevant to performance assessment of the potential Yucca Mountain repository are (CRWMS M&O 2000bn, Section 3.1.3.2.1.2):

- The relative response of nonsorbing tracers in fractured tuffs are consistent with matrix diffusion. This result supports the use of a dual-porosity conceptual model to describe radionuclide transport through the saturated, fractured rocks near Yucca Mountain.

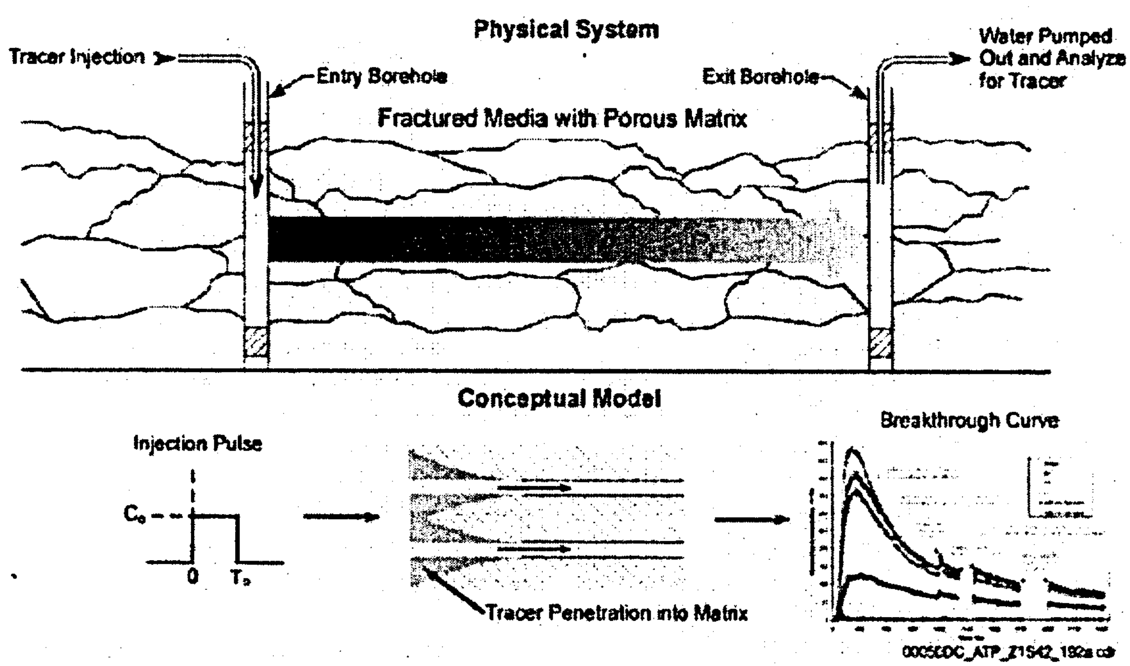


Figure 4-150. Physical System, Conceptual Model, and Normalized Tracer Responses from the Prow Pass Multiple Tracer Test
Source: CRWMS M&O 2000bn, Figure 3-8.

- Sorption of lithium ions (the sorbing radionuclide analogue) in the field was greater than or equal to measured sorption in the laboratory. Although lithium does not behave identically to any radionuclide, this result suggests that the use of laboratory-derived radionuclide sorption parameters in field-scale transport predictions is defensible and may even be conservative.

Other transport parameters derived from the C-Wells tracer tests include effective porosity, longitudinal dispersivities, matrix-diffusion mass transfer coefficients, colloid filtration and detachment rate constants, and horizontal anisotropy ratios. Conclusions related to these parameters are provided in *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (CRWMS M&O 2000eb, Section 6.9).

To simulate radionuclide transport through the site-scale model domain, a numerical approach for solving the mathematical equations describing solute transport is incorporated into the FEHM code. This numerical approach relies on the same computational grid developed for the site-scale saturated zone flow and transport model. The groundwater velocity field generated by that calibrated transport model provides the basis for predicting radionuclide migration through the site-scale model domain. Those factors that govern radionuclide mobility, including advection, dispersion, sorption, matrix diffusion, and colloid-facilitated transport, have been included in the transport model. The transport parameters used to model radionuclide transport were established during model abstraction for the TSPA analysis.

Mathematical Formulation of the Transport Model—Widely accepted mathematical equations describing the advective and dispersive transport provide the mathematical basis for the transport model. Matrix diffusion is incorporated into the mathematical formulation of the transport through the use of an analytical solution developed by Sudicky and Frind (1981) that describes transient contaminant transport in equally spaced parallel fractures. The model is a dual-porosity model for contaminant concentration that takes into account advective transport in the fractures, molecular diffusion from the fracture to the porous matrix, adsorption on the fracture face, and adsorption within the matrix. The model uses a no-flux condition at the midpoint of the matrix between fractures. The analytical solution requires the definition of a number of specific parameters, including the fracture aperture, the mean fracture spacing, the linear groundwater velocity within the fracture, the porosity of the matrix, the retardation factors in the matrix, and the effective matrix diffusion coefficient. Based on the values specified for these parameters, this analytical solution can be used to identify the distribution of a contaminant along the fracture at any point in time.

Sorption in the matrix is incorporated into the mathematical formulation of the transport model using a linear isotherm model (CRWMS M&O 2000bn, Section 3.3.2.3). Based on this linear isotherm model, distribution coefficients (K_d) are defined. These distribution coefficients identify the relative partitioning that will occur between the solid and liquid phases as radionuclides migrate through subsurface materials. The distribution coefficients may then be used to define retardation coefficients that identify the ratio of linear groundwater velocity to the retarded migration rate of radionuclides, based on the partitioning of radionuclides to subsurface materials.

Colloid-facilitated transport is incorporated into the mathematical formulation of the transport model in a manner similar to sorption (CRWMS M&O 2000bn, Section 3.3.2.4). The mathematical treatment for colloid-facilitated transport is focused on colloid attachment and detachment processes. The model conservatively assumes that in saturated fractured tuffs, colloids will move exclusively through fractures with negligible matrix diffusion and that colloid attachment and detachment to fracture surfaces can be described by first-order rate expressions. A local equilibrium assumption also has been adopted to describe these processes. Using these assumptions, an effective retardation factor for colloid transport through fracture tuffs can be defined based on a filtration rate constant, a detachment rate constant, and the fracture aperture. The mathematical model for colloid-facilitated transport in alluvium is identical to that for fractured tuffs, with the exception that the effective retardation factor for colloid transport is defined using alluvial attachment and detachment rates and the density and porosity of the alluvium.

Numerical Solution of Transport Equation—The numerical approach implemented in FEHM to obtain a solution for the transport equation was selected based on a number of important requirements (CRWMS M&O 2000bn, Section 3.3.4). The transport model needs to be able to handle extremes of the advective–dispersive transport that include a wide range of dispersivity values. It may be necessary for the transport model to simulate the transport of plumes that have smaller dimensions than the gridblock size of the flow model. The numerical approach used to solve the transport equation also must include a method for introducing the radionuclide source term into the model that is flexible enough to handle both small and large source regions at the water table. Finally, the numerical approach must be able to capture the important physicochemical processes known or suspected to occur as radionuclides migrate from the potential repository.

To meet these requirements, a particle-tracking method has been implemented in FEHM to provide a solution to the advection–dispersion transport equation (CRWMS M&O 2000bn, Section 3.3.4). In this approach, transport is decomposed into three interrelated components: advective, dispersive, and physiochemical. For the advective component, a particle-tracking method is used. A random-walk algorithm has been combined with the particle-tracking approach to account for the dispersive component of the advection–dispersion transport equation. To incorporate the dual-porosity transport and sorption components of transport equation, special modules have been incorporated into the FEHM code.

The particle-tracking method incorporated into FEHM is based on placing particles at specific points in the flow field to represent a specified mass of solute. These particles can be placed throughout the model domain to represent existing solute concentrations and can be introduced as necessary over time at specific source locations to represent radionuclide migration from the unsaturated zone. The particle-tracking method assumes a Lagrangian point of view, in which these particles move with the prevailing flow velocity. Based on a velocity field derived from the flow model, the trajectories for each particle are computed one at a time. Through a series of time steps, the particles are moved according to these computed trajectories.

The dispersive component of the transport is calculated using the random-walk method (Tompson and Gelhar 1990). This approach is based on the analogy between the mass transport equation and the Fokker–Plank equation of statistical physics (Van Kampen 1984). The dispersive displacement of each particle is computed using uniform random numbers, based on the dispersivity tensor and the porous flow velocity field at the particle location. In this model, the proper terms in the random-walk algorithm are derived from an anisotropic version of the dispersion coefficient tensor. During each time step, the trajectory of each particle is computed using the advective component of transport, which is modified through a series of displacements due to the dispersion calculated for each particle.

To incorporate the influence of matrix diffusion and sorption, the residence time transfer function particle-tracking method has been adapted to the particle-tracking algorithm (Zyvoloski et al. 1997a, pp. 41 to 42). In this method, adjustments to the transport time of a particle are made to account for the influence of physicochemical processes, such as sorption and matrix diffusion. During its path along a streamline, the particle transport time is governed by a transfer function describing the probability of the particle spending a given length of time on that portion of its path. The form of the transfer function is derived from an analytical or numerical solution to capture the appropriate processes being considered. The analytical solution identified above, matrix diffusion in fractured rock, and the retardation coefficients developed to account for sorption and colloid-facilitated transport are used by the model in developing the transfer function and determining the value of the delayed travel time along a path line for each particle resulting from the effects of matrix diffusion, sorption, and colloid-facilitated transport.

4.2.9.4 Total System Performance Assessment Abstraction

The saturated zone flow and transport component of the TSPA-SR evaluates the migration of radionuclides from their introduction at the water table below the potential repository to the accessible environment to the biosphere (Figure 4-128). This component of the analysis is coupled with the transport calculations for the unsaturated zone that describe the movement of contaminants in downward percolating groundwater from the potential repository to the water table. The input to the saturated zone flow-and-transport calculations is the spatial and temporal distribution of simulated mass flux at the water table that has been transported through the unsaturated zone. The transport of radionuclides in the saturated zone is linked to the biosphere analysis by the simulated time history of radionuclide concentration in groundwater at the accessible environment (Figure 4-151). Additional analyses have been done to evaluate the concentrations at the accessible environment. Radionuclide concentrations in the water are used in the biosphere component to calculate radiation dose rates received by the reasonably maximally exposed individual.

The site-scale saturated zone flow and transport model (CRWMS M&O 2000bn, Section 3) represents a synthesis of data on the groundwater flow system at the Yucca Mountain site, as well as information from regional-scale studies of the saturated zone. Key information used in the construction of the site-scale saturated zone flow model includes a three-dimensional representation of the geology of the system, water level measurements from wells, pumping tests of the volcanic units, hydrochemical data, and simulations of groundwater flux from the saturated zone regional-scale flow model. The calibration process for the site-scale saturated zone flow model provides an internally consistent representation of the saturated zone flow system that reproduces the key field observations of the system.

Information on radionuclide migration in the saturated zone is also incorporated in the site-scale saturated zone flow and transport model (CRWMS M&O 2000bn, Section 3). Key information incorporated into the model includes sorption coefficients for sorbing radionuclides, flowing interval spacing and porosity, matrix porosity in fractured volcanic units, effective porosity in alluvial units, dispersivity, and the effective diffusion coefficient. Additional data and inferences regarding colloid-facilitated transport of radionuclides are used in the site-scale saturated zone flow and transport model to simulate this process.

In the nominal case, migration of radionuclides from the unsaturated zone to the saturated zone is assumed to occur by undisturbed, natural movement of groundwater as recharge at the water table. Radionuclides migrating from the repository must be transported approximately 300 m (1,000 ft) downward by groundwater in the unsaturated zone to the water table, where they enter the saturated zone. Radionuclides are then carried downstream in the groundwater system. Radionuclides reach the accessible environment, where they could become a source of contamination in the biosphere (Figure 4-128).

Radionuclides may be dissolved in water or attached to colloids, as appropriate for the given radionuclide. Transport of parent radionuclides is simulated using the three-dimensional site-scale saturated zone flow and transport model (CRWMS M&O 2000bn, Section 3). Because the model is not currently formulated to simulate daughter products, the simultaneous transport of daughter products is carried out using a separate one-dimensional transport model (CRWMS M&O 2000el, Section 6.5). Reversible colloid transport, assuming equilibrium with the surrounding fluid, is simulated in the three-dimensional and one-dimensional transport calculations. A portion of the waste is vitrified, which produces colloids with irreversibly attached isotopes of plutonium and americium. The migration rate of these irreversibly sorbed colloids is retarded based on their expected rates of attachment and detachment in the fractured bedrock and alluvial materials. The total dose of any radionuclide computed in the assessment is the dose due to the sum of the above transported radionuclide mass through all forms of transport.

A number of processes contribute to the retardation of transported radionuclides and the dilution of the

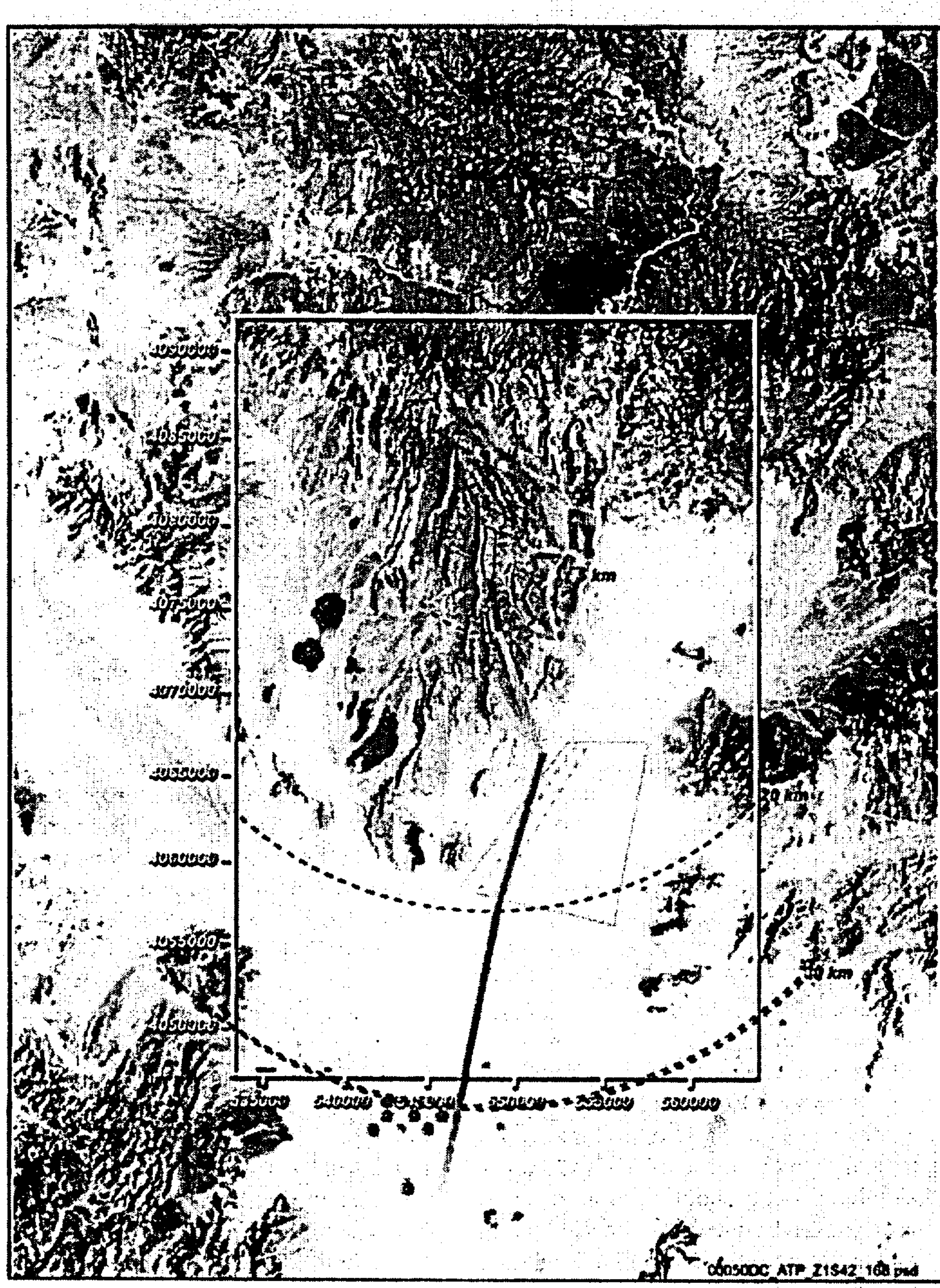


Figure 4-151. Map of Yucca Mountain Area with the Site-Scale Model Boundary
The multicolored line shows the generalized groundwater flow path from the one-dimensional saturated zone transport model, which provides the output of radionuclide mass at the exit of each pipe segment. See Figure 4-147 for a more detailed illustration of flow paths from Yucca Mountain. This analysis was performed to support the TSPA-SR. Source: Modified from CRWMS M&O 2000a, Figure 3.8-16.

radionuclide concentrations at the accessible environment downstream from Yucca Mountain. Important processes relevant to radionuclide transport in the saturated zone that are explicitly included in the TSPA-SR analyses are advection in groundwater, dispersion, matrix diffusion in fractured media, sorption of radionuclides, colloid-facilitated transport, radioactive decay, and radioactive ingrowth (production of radionuclides as decay products of other radionuclides during transport). Sorption of radionuclides is simulated to occur in the rock matrix of volcanic units but is conservatively disregarded in fractures of the saturated zone. Sorption of radionuclides is also simulated to occur in the porous media of the alluvium. Colloid-facilitated transport is included in the transport simulations as occurring in two modes: as irreversible attachment of radionuclides to colloids originating from the waste and as equilibrium attachment of radionuclides to colloids. Radioactive decay is simulated to occur for all radionuclides, and the effect of radionuclide ingrowth is simulated for the daughter radionuclides in four key decay chains in a separate one-dimensional saturated zone transport model (CRWMS M&O 2000el, Section 6.5).

The primary result of this synthesis is the site-scale saturated zone flow and transport model used for simulations of radionuclide transport in TSPA-SR analyses. This model includes modification of the final calibrated flow model (CRWMS M&O 2000ej) to accommodate variable parameter values for stochastic radionuclide transport parameters and consists of six alternative groundwater flow fields that incorporate uncertainty in groundwater flux and horizontal anisotropy. The site-scale saturated zone flow and transport model for TSPA-SR also produces simulation results in the appropriate format for coupling the radionuclide transport results with other components of the TSPA-SR analyses (CRWMS M&O 2000a).

Results of the site-scale saturated zone flow and transport model (CRWMS M&O 2000bn, Section 3.6.3) are abstracted by repeatedly performing simulations using a constant, unitary radionuclide mass flux corresponding to each radionuclide source considered for transport at the upstream end of the saturated zone. This process is done for each time step in the simulation. The calculations underlying this analysis were developed to provide insights about the sensitivities of saturated zone flow processes to individual flow parameters. The calculations were designed to accentuate and emphasize important saturated zone transport processes, and they are based on highly conservative representations of model components. In particular, the results illustrated in Figure 4-152 are based on a model that is appropriately conservative for TSPA analyses and not intended to represent expected breakthrough of radionuclides or groundwater travel time for the saturated zone portion of the Yucca Mountain flow system (CRWMS M&O 2000bn, Section 3.7.4). Accordingly, the breakthrough times are not a correct representation of the travel time of the water.

Groundwater carbon-14 data from well NC-EWDP-2D about 20 km (12 mi) downgradient from the repository along the groundwater flow path from the repository (Figures 4-131 and 4-133) offers a method of providing a rough travel-time estimate to the area of the accessible environment. Carbon-14 analyses (CRWMS M&O 2000eg, Section 6.5.7.2.2) indicate a minimum groundwater age of about 7,900 years.

In order to estimate the time required for water to move from the potential repository to the environment, the time required for flow from the point of recharge at the ground surface to the repository must be subtracted from the total age. Assuming that rapid fracture flow through the welded units results in negligibly small travel times through these units and that most of the travel time from between the ground surface and repository horizon is the result of slow matrix flow through the nonwelded tuffs of the Paintbrush nonwelded hydrogeologic unit (PTn), the travel time through the PTn can be calculated from the average moisture content of rocks in the PTn (20 percent) and the PTn thickness. The PTn ranges in thickness from about 100 m (330 ft) to 25 m (80 ft). Complete piston displacement of the in situ water is assumed in order to maximize the estimated travel time through the PTn. The water column heights of 20 m (66 ft) (for a 100-m [330-ft] thick PTn) and 5 m (16 ft) (for a 25-m [80-ft] thick PTn) are divided by the average flux over the repository

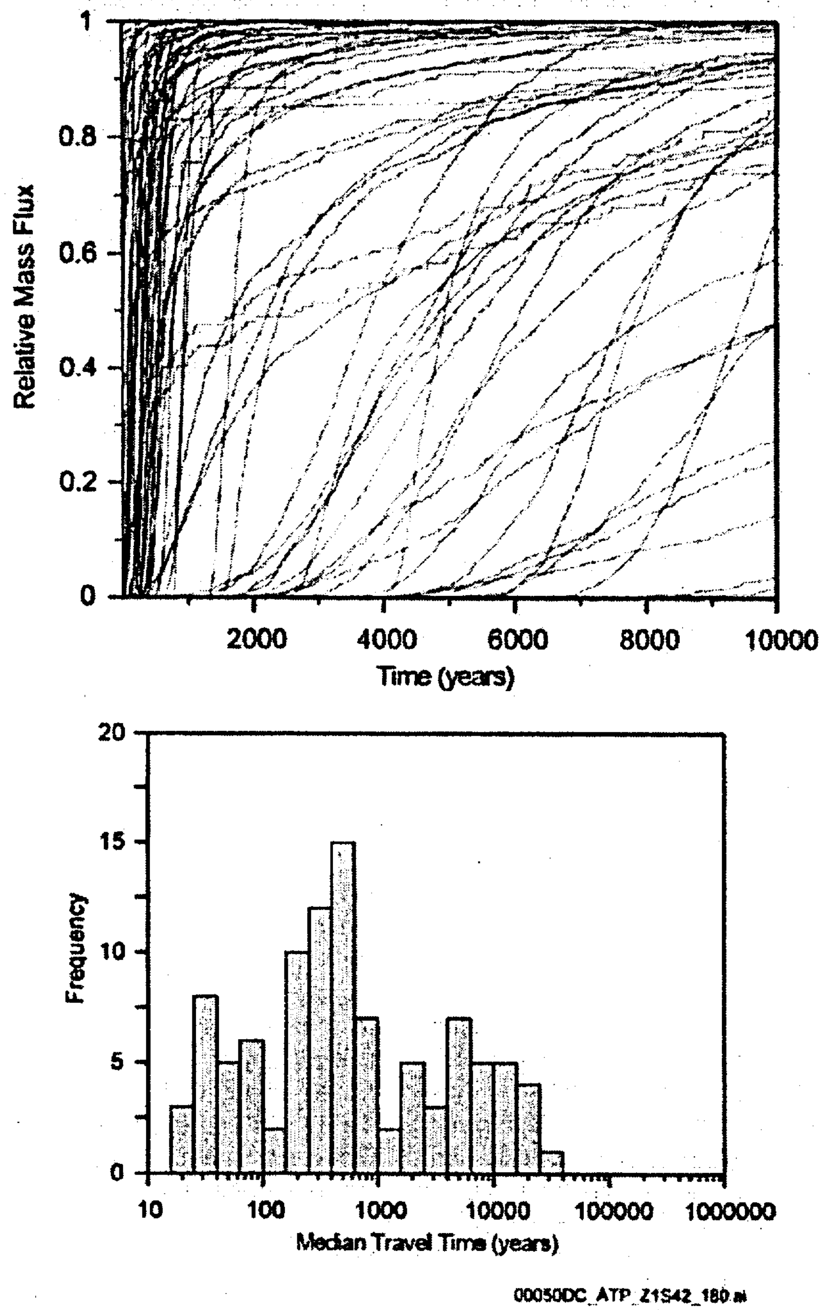


Figure 4-152. Representative Breakthrough Curve and Histogram

In this case, the simulated unit breakthrough curves and histogram of median transport times of mass flux were generated for carbon. Additional curves are presented in *Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA* (CRWMS M&O 2000el, Section 6.3.2). The data shown in this figure are based on a model that is appropriately conservative for TSPA analyses and not intended to represent expected breakthrough of radionuclides or groundwater travel time for the saturated zone portion of the Yucca Mountain flow system. Source: CRWMS M&O 2000bn, Figure 3-31.

(5 mm/yr or 0.005 m/yr [0.2 in./yr]) resulting in estimates of travel time from the ground surface to the potential repository that range from approximately 1,000 to 4,000 years.

Subtracting these values from the groundwater carbon-14 ages provides a rough estimate of 3,900 to 6,900 years for travel time from the potential repository to the environment. This range represents an averaged duration that is generally consistent with the results of groundwater flow models. Although the carbon-14 data do not preclude the existence of some faster flow paths, it suggests that on average, the time required for water to move from the potential repository to the environment is on the order of thousands of years.

The radionuclide mass breakthrough curves at the downstream end of the saturated zone contain information about the model behavior for those source and receptor locations, assuming steady groundwater flow (Figure 4-152). The radionuclide mass breakthrough curves are saved for later computation of radionuclide mass transport by the TSPA-SR simulator. These computations are performed by scaling the mass breakthrough for a source by the mass input at each time step. In this way it is unnecessary to perform flow simulations when only the mass input for a radionuclide changes (i.e., for changes in the source or transport through the unsaturated zone).

The source of radionuclide contamination entering the site-scale saturated zone flow and transport model is specified as a point within each of four source regions beneath the potential repository (CRWMS M&O 2000bn, Section 3.6.3.4.1). The point source is located at an elevation of 725 m (2,380 ft) above mean sea level in the nominal case, which is approximately 5 m (16 ft) below the water table over most of the area beneath the potential repository. The horizontal location of the point source in each of the four source regions varies stochastically from simulation to simulation, reflecting uncertainty in the location of leaking waste packages and transport pathways in the unsaturated zone. Radionuclide transport simulations with the site-scale saturated zone flow and transport model are performed using 4,000 particles, 1,000 of which are released at each of the four point source locations at the beginning of the simulation. The mass of radionuclide for each particle was not varied during the simulations.

Radionuclide transport is directly simulated for radionuclides (except the products of radioactive decay and ingrowth) using the site-scale saturated zone flow and transport model (CRWMS M&O 2000bn, Section 3.6.3). The convolution integral method is used in the TSPA-SR calculations to determine the time-varying radionuclide mass flux at the interface of the saturated zone and the biosphere, downgradient from the potential repository (Figure 4-153). This method combines information about the response of the system, as simulated by the site-scale saturated zone flow and transport model, with the radionuclide source history from the unsaturated zone to calculate transient system behavior. The most important assumptions of the convolution integral method are linear system behavior and steady-state flow conditions in the saturated zone. The two inputs to the convolution integral method are a radionuclide mass breakthrough curve in response to a unit step-function mass flux source as simulated by the site-scale saturated zone flow and transport model and the radionuclide mass flux history as simulated by the unsaturated zone flow and transport model (CRWMS M&O 2000c, Section 3.11). The output is the radionuclide mass flux history at the biosphere.

The presence of faults and fracture zones that are not explicitly represented in the site-scale saturated zone flow and transport model (CRWMS M&O 2000bn, Sections 3.3.6.3 and 4.2.1.2) and their potential impact on groundwater flow is implicitly included in the nominal case through consideration of horizontal anisotropy of the permeability in the fractured volcanic units downgradient of the potential repository. There is uncertainty in the potential anisotropy of permeability in the horizontal direction over the scale of the transport path length. Given the uncertainty in anisotropy, and to simplify the model, the potential effects of anisotropy are bounded by setting the anisotropy ratio to 1 (isotropic) or 5 (anisotropic), values that are based on the results of tests at the C-Wells Complex at Yucca Mountain (Winterle and La Femina 1999, Section 4.5).

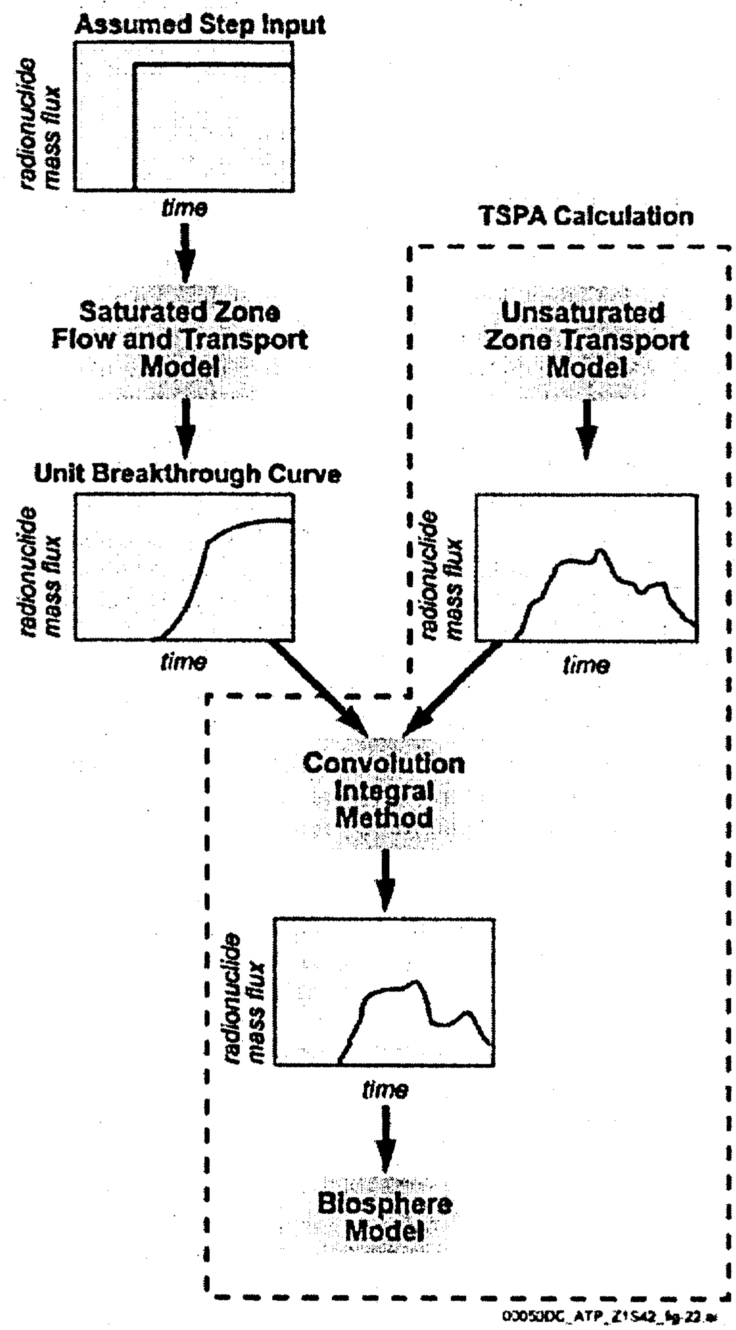


Figure 4-153. Convolution Integral Method Used in Saturated Zone Flow and Transport Calculations for Total System Performance Assessment–Site Recommendation

The dashed line is to distinguish between the saturated zone flow and transport model calculation and the TSPA-SR calculation. The TSPA-SR calculation is explained in Section 4.4.1. This figure only reflects a portion of the complete TSPA-SR calculation. Source: CRWMS M&O 2000bn, Figure 3-28.

Features, events, and processes, or FEPs (Freeze et al. 2001), include expected behavior and scenarios outside of the expected behavior of the repository, which could result in significant changes in radionuclide release to the biosphere. An example of a FEP is the possible eruption of a volcano in the Yucca Mountain area. Saturated zone flow and transport for the TSPA-SR explicitly incorporates many FEPs of the saturated zone system and implicitly includes others (CRWMS M&O 2000bn, Section 1.3). Those FEPs that are implicitly incorporated are primarily captured in the range of uncertainty assigned to parameters varied in the stochastic analyses. The most important features of the saturated zone system that are explicitly represented in the simulations are the geometry and variability in properties among hydrogeologic units in the subsurface. Of particular importance is the distinction between units consisting of fractured volcanic rock media and those that consist of porous media (alluvium). In addition, numerous hydrologic features corresponding to faults and geologic zones are explicitly incorporated into the site-scale saturated zone flow and transport model as part of the calibration process.

For the nominal TSPA-SR case (CRWMS M&O 2000bn, Section 3.7), analyses of saturated zone flow and transport incorporate uncertainty in the saturated zone groundwater flow system and in horizontal anisotropy. Uncertainty in groundwater flow is incorporated through the use of six discrete flow fields. The six fields correspond to low, average, and high flux crossed with either isotropic or horizontal anisotropic (5:1 north–south) permeability to consider uncertainty in the magnitude of groundwater flux and horizontal anisotropy. The effect of the assumption of anisotropy (5:1 north–south) does not result in a large change in the transport paths.

Climate-change forecasts for Yucca Mountain based on the analysis of past climate changes and on the assumption that climate is cyclical (USGS 2000a) are used to predict future infiltration at Yucca Mountain. Climate change is explicitly included in the nominal case of saturated zone flow and transport for TSPA-SR. Increases in the groundwater flux of the saturated zone for a monsoonal climate state (forecast to occur in about 400 to 600 years and to have a duration of 900 to 1,400 years) and the glacial-transition climate state (forecast to occur after the monsoonal climate and to persist beyond 10,000 years) are included in the analyses. For conservatism, the impact of a rising water table on groundwater flow paths in the saturated zone is not explicitly included in the saturated zone flow and transport model for the nominal case. This is conservative because radionuclides are transported in shallow flow paths at the water table, and a rising water table would result in those flow paths rising up and radionuclides being transported in less permeable material and with a slower travel time. Thus, the current model, which ignores the impact of a rising water table on groundwater flow paths and transit time, produces transport times that are conservative with respect to dose.

Multiple simulations of the saturated zone transport model are performed using continuous distributions for the parameters that define the transport characteristics of the saturated zone system. The probabilistic analysis of uncertainty is implemented through Monte Carlo simulations of the saturated zone flow and transport system in a manner consistent with the TSPA-SR simulations implemented with the GoldSim software code. Alternative models of groundwater flux and horizontal anisotropy are included as the six saturated zone groundwater flow fields. Uncertainty in the location of the contact between volcanic units and the alluvium is incorporated as geometric variability in the alluvium zone in the site-scale saturated zone flow and transport model. Colloid-facilitated transport is considered in the uncertainty analysis through the use of two coexisting modes of colloid-facilitated transport.

In general, parameters to which the model results are sensitive, due to the combination of the numerical importance of the parameter in the model or the uncertainty in the parameter value, are represented stochastically. Parameters to which the model results are not sensitive are represented by constant values. This approach is a reasonable simplifying assumption because the results are not significantly altered by those parameters.

The following parameters are considered either wholly or partially stochastic:

- Groundwater specific discharge
- Alluvium boundary
- Effective porosity in the alluvium
- Flowing interval spacing, flowing interval porosity
- Effective diffusion coefficients
- Bulk density
- Sorption coefficients
- Longitudinal dispersivity
- Horizontal anisotropy
- Source region definitions
- Retardation of radionuclides irreversibly sorbed on colloids (volcanics and alluvium)
- Retardation of radionuclides reversibly sorbed on colloids.

The stochastic distributions and constant values used in the site-scale saturated zone flow and transport model for TSPA-SR are presented in *Uncertainty Distribution for Stochastic Parameters* (CRWMS M&O 2000ek, Section 6). Matrix porosity, a parameter used in matrix diffusion, is recognized as an uncertain parameter. Matrix diffusion is very sensitive to flowing interval spacing and matrix-diffusion coefficient but not sensitive to matrix porosity. As a result, matrix porosity was treated as a constant value in all TSPA simulations.

For the purposes of the TSPA-SR model, the breakthrough curves of radionuclide mass arrival at the accessible environment are simulated with the site-scale saturated zone flow and transport model by obtaining output of particle travel time from the FEHM code when a particle crosses a fence of nodes in the model grid. Three fences, corresponding to travel distances of 5, 20, and 30 km (approximately 3, 12, and 19 mi), are specified for output of breakthrough curves. These fences of grid nodes are located at the prescribed distance from the southern corner of the outline of the potential repository and extend from the upper surface to the lower surface of the site-scale saturated zone flow and transport model domain. The saturated zone groundwater flow pathway from beneath the potential repository extends in a generally southerly direction and all particles are counted as they cross the intervening fences of grid nodes. The model setup of the one-dimensional saturated zone transport model provides output of radionuclide mass at the exit of each pipe segment, and these segments are constructed to end at distances of 5, 20, and 30 km (approximately 3, 12, and 19 mi) (Figure 4-151).

The contributions of radionuclide mass flux at the 20-km (12-mi) fence from the four source regions in the site-scale saturated zone flow and transport model are summed to obtain the total radionuclide mass flux for a time step in the TSPA-SR simulator. Summing these values of radionuclide mass flux occurs following the convolution integral calculation. The mass flux of the daughter radionuclides from the one-dimensional saturated zone transport model is also included in the calculation at this point.

Radionuclide concentrations in groundwater are used in the biosphere component of the TSPA-SR analysis to calculate radiological dose to the receptor of interest using biosphere dose conversion factors. The concentrations of radionuclides are calculated by dividing the radionuclide mass delivered to the biosphere per year for that time step by the total groundwater use per year of the receptor of interest.

Additional breakthrough curves were calculated for a location consistent with NRC licensing-related regulations at 10 CFR Part 63 (66 FR 55732), which provide a new definition of the boundary between the controlled area and the accessible environment. This location was evaluated where the hypothetical reasonably maximally exposed individual is assumed to live at the point above the highest concentration of radionuclides in the simulated plume of contamination where the plume crosses the southernmost boundary of the controlled area (at a latitude of 36° 40' 13.6661" North) and reaches the accessible environment. This distance is approximately 18 km (11 mi) from the repository footprint, compared to the original distance of approximately 20 km (12 mi) used in the saturated zone transport modeling calculated for the TSPA-SR model. To provide a preliminary assessment consistent with the final NRC regulation at 10 CFR Part 63, a conservative sensitivity analysis was performed for a nonsorbing radionuclide and a sorbing radionuclide (carbon-14 and neptunium-237, respectively) to evaluate how long radionuclides are projected to take in being transported from the saturated zone directly beneath the potential repository to a downgradient location where they could enter the accessible environment (BSC 2001a, Section 12.5.3). These radionuclides were chosen because they are representative of the solutes that would be most rapidly transported (i.e., nonsorbing carbon-14) or are among the larger contributors to the potential dose (i.e., neptunium-237), and together they bound the range of solute transport.

The sensitivity analysis was conducted using the saturated zone flow and transport model with conservative values for process model parameters. The results of comparisons between the different transport distances for a nonsorbing radionuclide (carbon-14, which is representative of other nonsorbing radionuclides such as technetium-99 and iodine-129) and a slightly sorbing radionuclide (neptunium-237) are illustrated in Volume 1, Section 12.5.3 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a). The simulated radionuclide breakthrough curves at 18 km (11 mi) have shorter radionuclide transport times than those at 20 km (12 mi) (BSC 2001a, Section 12.5.3) under the same set of conservative assumptions.

The effect of the reduced advective transport times (due to the shorter distance) is to shift the breakthrough curves to correspondingly earlier times (BSC 2001b, Section 5.4). During the time period of regulatory concern (10,000 years), when the doses are dominated by low-probability early waste package failures (due to improper heat treatment of the closure welds), the releases and resulting doses are primarily related to nonsorbing radionuclides (BSC 2001b, Section 3.2.5). Therefore, reducing the advective transport time would reduce the breakthrough of the radionuclides by roughly the same amount of time. This reduction would have no effect on the magnitude of the peak mean annual dose because this is controlled by the temporally dispersed release from the engineered barrier system (BSC 2001b, Section 5.4).

Additional saturated zone breakthrough curves, which describe the time-related arrivals of radionuclides at the reasonably maximally exposed individual location, were calculated in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a) to evaluate long-term performance with respect to the criteria established in 10 CFR Part 63 (66 FR 55732). The saturated zone breakthrough curves were used in analyses to simulate radionuclide transport from the water table beneath the potential repository to the reasonably maximally exposed individual location at the accessible environment. The simulated radionuclide breakthrough curves at the reasonably maximally exposed individual location exhibited shorter transport times than those used in *Supplemental Science and Performance Analyses* (BSC 2001a, Section 12.3.2.3) on a realization-by-realization basis. In particular, those radionuclides that may have significantly greater sorption in the alluvium than in the volcanic units (e.g., neptunium-237) exhibit shorter transport times to the reasonably maximally exposed individual location in this analysis relative to the location used in analyses for *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a). This result is related to the fact that the reasonably maximally exposed individual location in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a) results in a decrease in the length of transport through the alluvium relative to the previously computed transport path.

4.2.10 Biosphere

The biosphere is the ecosystem of the earth and the organisms inhabiting it and includes the soil, surface waters, air, and all living organisms. The purpose of the TSPA-SR biosphere analyses is to develop dose conversion factors reflecting the transport and retention of radionuclides within the biosphere. These dose conversion factors, called biosphere dose conversion factors, are subsequently used directly in the TSPA abstraction to calculate dose. The biosphere analyses are designed to provide the capability to predict radiation exposures to persons living in the general vicinity of the potential repository if there is release of radioactive material to the biosphere after closure of the repository (CRWMS M&O 2000a, Section 3.9). Analysis of the biosphere transport and uptake processes requires conceptually interpreting the important contaminant transport pathways (ways in which potential releases from a geologic repository could reach a human being and result in a radiation dose) (CRWMS M&O 2000bo, Section 3.1.4).

4.2.10.1 Conceptual Basis

The biosphere is the last component in the chain of TSPA component models considered in the overall performance assessment of the potential repository site (Section 4.2). Upstream from the biosphere, there are two connections: (1) the biosphere is coupled to the saturated zone flow and transport model for the contaminated groundwater use scenario (nominal case); and (2) the biosphere is coupled to the volcanic dispersal model for the direct volcanic release scenario.

The biosphere component of TSPA analyses addresses processes and pathways that could either disperse or concentrate radionuclides released from the repository. The biosphere analyses focus on the behaviors (i.e., lifestyles, including dietary and activity habits) that would be significant to radiation exposure and the environment around these potentially exposed people that would be important to their radiation exposure (Figure 4-154) (CRWMS M&O 2000bo, Section 3.1.2). For the TSPA-SR model and the supplemental TSPA model, the conceptual basis for the biosphere component is consistent with the proposed rules promulgated by the NRC and EPA (BSC 2001a, Section 13.1; BSC 2001b, Section 3.2.11). With the promulgation of the final rules by each agency, additional biosphere model sensitivity and supplemental performance analyses evaluate the potential impacts consistent with the final licensing-related rules (Williams 2001a, Section 5.2.5; Williams 2001b, Section 6.3).

The biosphere analyses for the TSPA-SR model considered a hypothetical human receptor to evaluate the effects of the potential contaminant pathways and processes, consistent with proposed regulations. Subsequent biosphere analyses are based on the receptor concept of the reasonably maximally exposed individual consistent with 40 CFR 197.21 and 10 CFR 63.312 (66 FR 55732).

There have been four prior TSPA iterations conducted for the disposal of spent nuclear fuel and high-level radioactive waste at Yucca Mountain (Eslinger et al. 1993; CRWMS M&O 1994; 1995; 1998g, Chapter 9). The TSPA-VA was the first effort by the DOE to incorporate an all-pathway biosphere model for radiation dose assessment (CRWMS M&O 1998g, Chapter 9). With a few changes, the approach developed for *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998) is used in the TSPA-SR.

Changes incorporated into the TSPA-SR analyses include the following:

- A comprehensive list of FEPs is used to identify the attributes of the conceptual biosphere pathway analyses (CRWMS M&O 2000bo, Section 3.1.3).
- The receptor and the reference biosphere concepts specified by the regulatory agencies are used in calculations.
- Radionuclide buildup in soils resulting from continued irrigation with contaminated groundwater is considered in the analyses, and estimates of soil and radionuclide removal by erosion are incorporated into overall dose calculations.
- An assessment of the annual water usage by a hypothetical farming community was conducted.

In TSPA-SR, the two basic scenarios for radionuclide transport to the biosphere are analyzed as the following:

- Use of contaminated groundwater for domestic and agricultural purposes

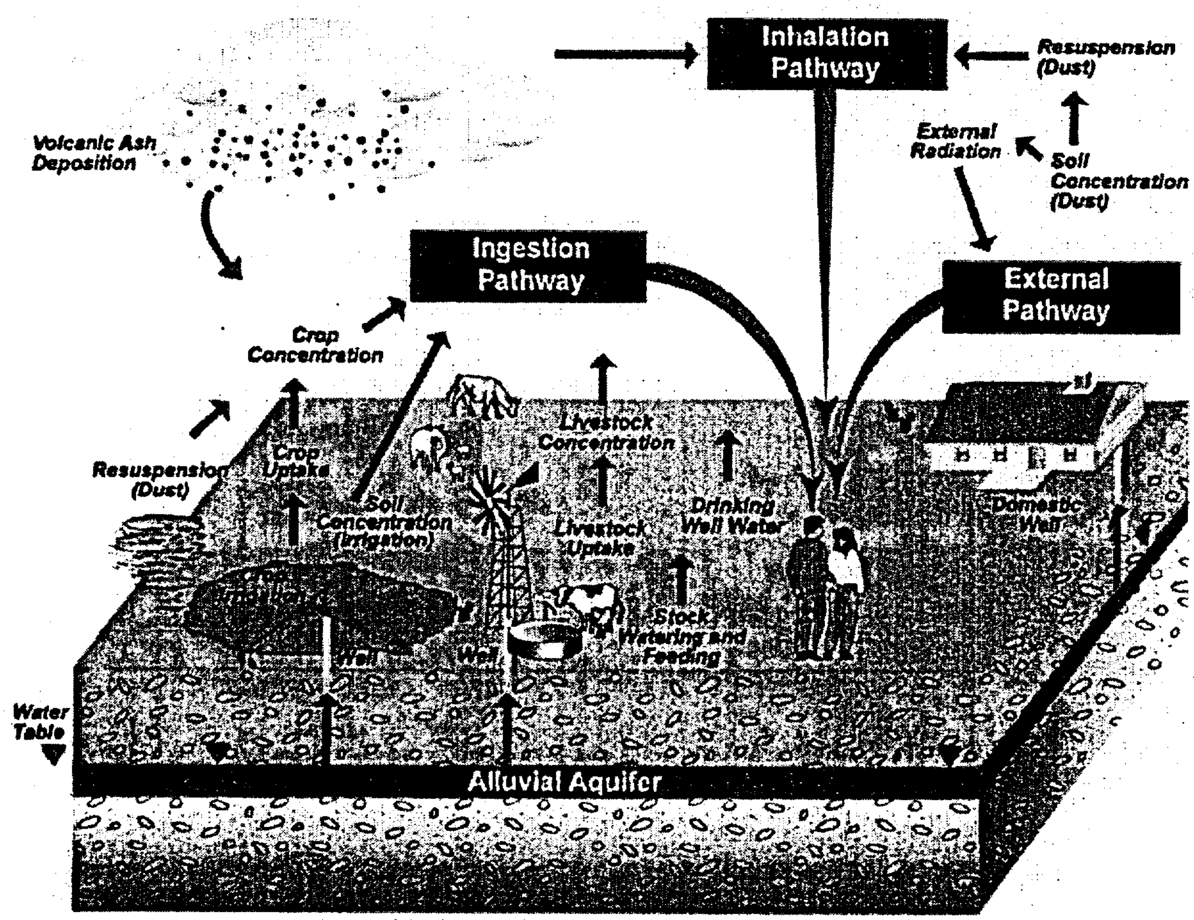


Figure 4-154. Illustration of the Biosphere Transport Pathways and Processes Contributing Dose to the Biosphere Receptor(s)

- Dispersal of radionuclide contaminants onto the earth's surface by a direct volcanic release (ash deposition).

The TSPA-SR biosphere analyses include a conceptual representation of the local population, as receptors, and contaminant transport pathways, represented as a mathematical expression. GENII-S (Leigh et al. 1993), a computer code for predicting radiation dose, is used to calculate radionuclide-specific biosphere dose conversion factors. The biosphere dose conversion factors consider the pathways of radionuclides (Figure 4-154) through the environment (such as irrigation and uptake of a contaminant by food crop plants and the subsequent ingestion of the plant by the person in question). GENII-S calculates a biosphere dose conversion factor for each of the radionuclides considered in the analysis by assuming a unit concentration of that radionuclide in water and then evaluating radionuclide transfer through pathways to the human receptor (CRWMS M&O 2000bo, Section 3.2.1). In other words, this computer program calculates a factor by which scientists can estimate a receptor's annual committed dose from the release of a particular radionuclide into the biosphere. The multiplication factor calculated by GENII-S is determined using input parameters that characterize radionuclide transport in the biosphere and human exposure. Human exposure parameters include the amount of groundwater the person drinks and the amount of locally grown foodstuffs (both animal and vegetable) the person consumes. The conversion factors also include such lifestyle elements as the amount of time spent outdoors (CRWMS M&O 2000bo, Sections 3.1 and 3.3). Once a conversion factor for a particular radionuclide is determined, it can be multiplied by the actual radionuclide concentrations in groundwater (determined by the saturated zone flow and transport modeling component of the TSPA-SR) to calculate the dose the person(s) would receive.

Many of the input parameters used in the biosphere analyses (e.g., quantity of groundwater and locally produced foodstuffs ingested annually) were obtained through a survey of inhabitants residing within an 80-km (50-mi) grid centered on Yucca Mountain (CRWMS M&O 2000bo, Section 3.2.4). The survey was designed to permit an accurate representation of dietary patterns. Over one thousand interviews were completed for the survey. A detailed discussion of the survey method and the confidence levels of the resulting data is found in *The 1997 "Biosphere" Food Consumption Survey Summary Findings and Technical Documentation* (DOE 1997d). Lifestyle characteristics, including employment attributes, of the inhabitants in the area were determined based on 1990 Census Data (Bureau of the Census 1999). Based on existing employment classifications, the highest exposure due to outdoor employment activity would be for agricultural or construction workers. A major portion of the data related to the surface soil layer considered in the analyses was obtained from a U.S. Department of Agriculture Natural Resource Conservation Service database that provides chemical and physical properties for the soils for southern Nye County, including the Amargosa Valley (CRWMS M&O 2000eo, Section 4.1, Table 1). Other data used in biosphere pathway analyses were obtained from credible literature sources, including refereed journal articles (CRWMS M&O 2000bo, Section 3.2.4).

It is important to note that the biosphere pathway analysis component of the TSPA-SR does not, in itself, perform dose assessment calculations (CRWMS M&O 2000bo, Section 3.1.2.1). Rather, the biosphere analyses provide the capability to the integrated TSPA model to calculate dose to the human being considered most at risk once radionuclide concentrations in the groundwater and volcanic ash have been determined through the calculations of the other performance assessment subsystem component models (e.g., unsaturated zone flow and transport, saturated zone flow and transport).

Receptor Concepts—For the TSPA-SR model, project scientists determined a critical group representing those individuals in the general population who, based upon conservative assumptions, are expected to receive the highest potential doses in the event of radionuclide release from the repository. As discussed previously, the biosphere pathway analyses for TSPA-SR were conducted for the hypothetical receptor called the average member of the critical group (consistent with proposed 10 CFR Part 63 [64 FR 8640]). Supplemental TSPA analyses were conducted consistent with the receptor in the EPA standard and NRC regulations, which is identified as a "reasonably maximally exposed individual." Consistent with the final rules, the reasonably maximally exposed individual is the hypothetical person who would:

- Live in the accessible environment above the highest concentration of radionuclides in the plume of contamination
- Have a diet and living style representative of the people who now reside in the Town of Amargosa Valley, Nevada. The DOE must use projections based upon surveys of the people residing in the Town of Amargosa Valley, Nevada, to determine their current diets and living styles and use the mean values of these factors in the assessments
- Use well water with average concentrations of radionuclides based on an annual water demand of 3,000 acre-ft
- Drink 2 L (0.53 gal) of water per day from the wells drilled into the groundwater at the reasonably maximally exposed individual location in the accessible environment
- Is an adult with metabolic and physiological considerations consistent with present knowledge of adults.

Comparison of the biosphere model results for the receptor indicates that the dose conversion factors calculated for the average member of the critical group adequately represent the potential exposure for the reasonably maximally exposed individual (Williams 2001a, Section 5.2.5).

4.2.10.2 Summary State of Knowledge

Reference Biosphere—The climate in the vicinity of Yucca Mountain is arid, and the site is located within the sparsely populated region between the Great Basin and the Mojave deserts in southern Nevada. The natural vegetation is predominantly desert scrub and grasses (CRWMS M&O 2000bo, Section 3.1.1.1).

The nearest community in the direction of groundwater flow from the potential repository site is the Town of Amargosa Valley (Figure 4-155). The Town of Amargosa Valley is an area of approximately 1295 km^2 (500 mi^2) that was defined as a tax district by the Nye County commissioners in the early 1980s. The closest inhabitants to Yucca Mountain are within Amargosa Valley, approximately 20 km (12 mi) south at the intersection of U.S. 95 and Nevada State Route 373, a location known as Lathrop Wells (there are approximately eight inhabitants at this location) (CRWMS M&O 2000bo, Section 3.1.1.3). This area is near the location of the reasonably maximally exposed individual in the accessible environment at the southernmost boundary of the potential repository controlled area (Williams 2001a, Section 5.2.3). The Amargosa Farms area (a triangle of land bounded by the Amargosa Farm Road to the north, Nevada State Route 373 to the east, and the California border running from the northwest to the southeast) is the closest agricultural area.

The Amargosa Valley area is sparsely populated and primarily rural agrarian in nature. The area supports a population of approximately 900 in about 450 households (DOE 1997d, Section 2.4). Agricultural activity is directed primarily towards livestock feed production (e.g., alfalfa; see Figure 4-155b), but gardening and animal husbandry are common. Water for both domestic and agricultural use is taken from local wells, mostly privately owned. Commercial agriculture in the Amargosa Valley farming triangle includes a dairy operation (approximately 4,500 milk cows) employing about 50 people, a catfish farm that sustains approximately 15,000 catfish, and a garlic farm that annually produces about one ton of garlic per year. Approximately 728 hectares (1,800 acres) are dedicated to alfalfa production, 12 hectares (30 acres) to oats production, 32 hectares (80 acres) are in pistachios, and 4 hectares (10 acres) in grape vineyards. The area has a general store (Figure 4-155c), community center, senior center, elementary school, public library, medical clinic, restaurant, hotel-casino, and motel (CRWMS M&O 2000bo, Section 3.1.1.3).

Previous TPSA analyses have shown that, given the lifestyle habits in the Amargosa Valley, the greatest potential contributors to dose are the drinking of contaminated groundwater and the consumption of locally produced leafy vegetables (DOE 1998, Volume 3, Section 3.8.3.1).

Groundwater Demand—TSPA-SR and *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a) used an average water demand of about 2,000 acre-ft (a mean of 1,938 acre-ft with a range from 887 to 3,367 acre-ft) (CRWMS M&O 2000bo, Section 3.4.6) based on a survey of current usage. Consistent with the final 10 CFR 63.312(c) (66 FR 55732), revised supplemental TSPA analyses assumed the use of 3,000 acre-ft/yr. This higher water demand results in a subsequent decrease in expected mean annual dose via the groundwater pathway (Williams 2001b, Section 6.3).

In the TSPA-SR analyses, the input parameter defining the quantity of drinking water consumed by the receptor was based upon human consumption data obtained by the survey of the Amargosa Valley area; this value is 753 L/yr (199 gal/yr), or 2.1 L/day (0.55 gal/day) (CRWMS M&O 2000ep, Table 4; CRWMS M&O 2000a, Section 3.9.1). Consistent with final licensing-related NRC regulations, the daily drinking water consumption value for the receptor is 2 L/day (0.53 gal/day) (730 L/yr [193 gal/yr]) (10 CFR 63.312(c) [66 FR 55732]).

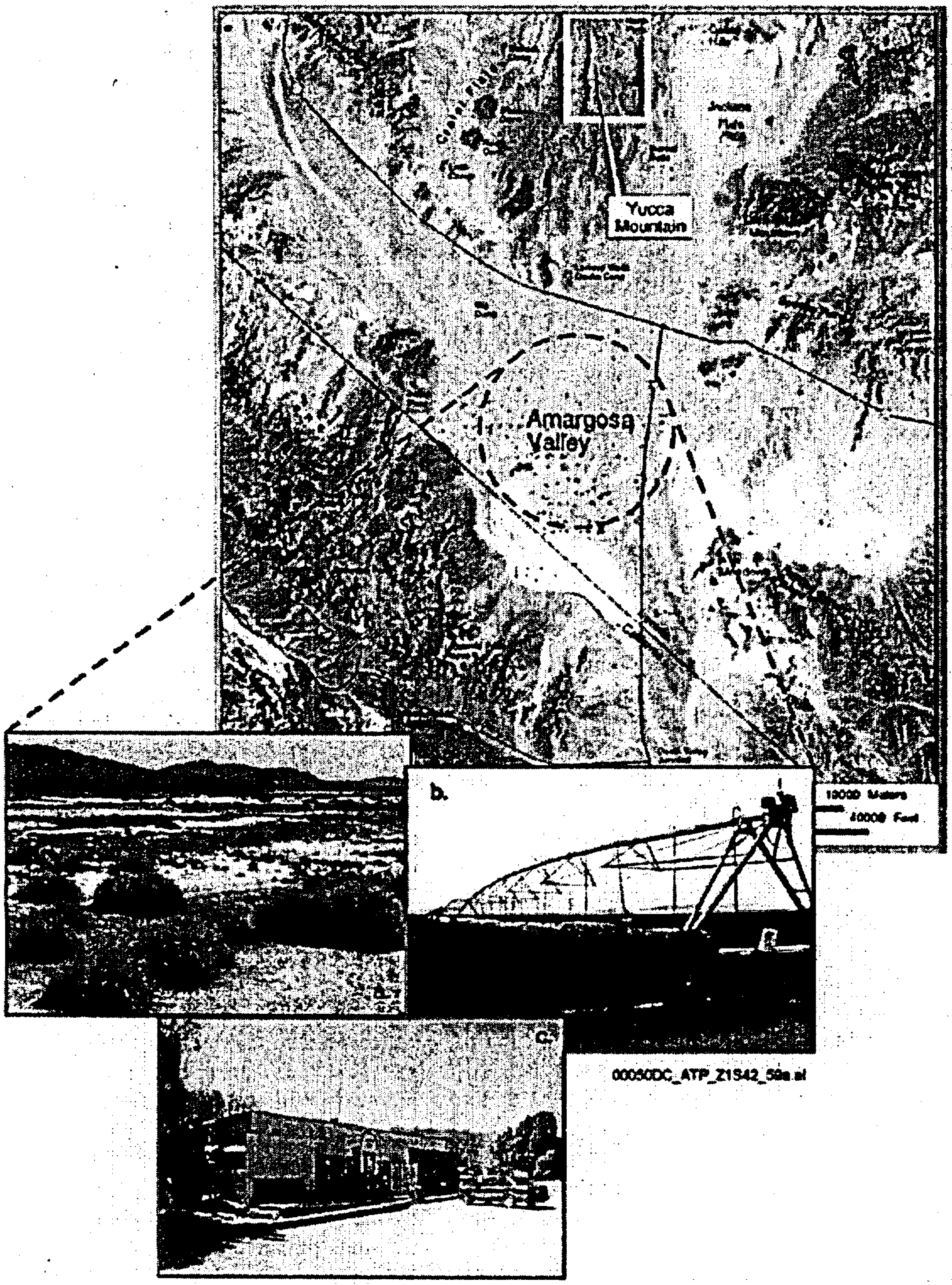


Figure 4-155. Satellite Image Showing the Yucca Mountain Area, Including the Amargosa Valley, with Details of the Area

(a) Characteristic sparsely vegetated desert grassland/shrubland in undeveloped areas. (b) Alfalfa produced with groundwater distributed through sprinkler irrigation is the dominant agricultural practice. (c) General store in Amargosa Valley. Source: Modified from CRWMS M&O 2000a, Figures 3.9-3 and 3.9-4.

The 2 L/day (0.53 gal/day) drinking water consumption value used in the supplemental biosphere analyses is slightly less than the 2.1 L/day (0.55 gal/day) used in TSPA-SR model and has minimal impact on the biosphere dose conversion values used for supplemental TSPA model analyses (Williams 2001a, Section 5.2.5).

4.2.10.3 Process Model Development and Integration

4.2.10.3.1 Biosphere Process Model

As described earlier, the biosphere conceptual model is a set of hypotheses consisting of assumptions, simplifications, and idealizations that describe the essential aspects of the biosphere in the vicinity of Yucca Mountain. This conceptual model is used to evaluate the transport of radionuclides potentially released from the source (repository) throughout the environment to the receptor of interest, as well as internal and external exposure of the receptor to the radionuclides present in the environment.

Two repository release scenarios are evaluated: (1) pumping of contaminated groundwater to be used for both domestic and agricultural purposes by the receptor under nominal repository performance; and (2) deposition of contaminated ash resulting from a volcanic (igneous activity) release from the repository (CRWMS M&O 2000bo, Section 3.1.5).

The biosphere conceptual model includes the following components: the surface soil above the lower bounds of the plant root zone (including volcanic ash, in the case of a volcanic eruption), the surface water (e.g., large, man-made containers filled from groundwater sources), the atmosphere, and flora and fauna. Thus, the biosphere includes biological components that may be a part of the various potential pathways for radionuclide transport to humans. The upper boundary of the biosphere includes that portion of the atmosphere that controls the transport and dispersal of airborne radionuclides. For the TSPA-SR, the effects of surface soil removal by erosion or other processes (e.g., mechanical removal as in harvesting of soil along with crop) was estimated based upon land use and conservation practices. The objective for considering the effects of surface soil removal was to allow for the evaluation of radionuclide buildup in soil following continuous irrigation with contaminated groundwater (CRWMS M&O 2000eq, Section 7.3).

After the permanent closure of the potential repository, radionuclides may eventually be leached to the underlying groundwater, or saturated zone, and then migrate hydrologically downgradient to the location beneath the receptor. This water could then eventually reach the earth's surface through the pumping of well water (CRWMS M&O 2000bo, Section 3.1.4.2).

Potential cooler, wetter future climate (glacial-transition) could effect biosphere pathways and performance assessment. A climate evolution pathway analysis to evaluate the potential effects on the biosphere model resulted in a reduction in expected biosphere dose conversion factor values for the future climate (BSC 2001a, Section 13.3.7). The TSPA-SR and supplemental TSPA models use the modern climate condition biosphere model (CRWMS M&O 2000bo, Section 3.1.1) because it is more conservative than the evolved climate model.

In the contaminated groundwater use scenario, a groundwater well is considered the source of drinking and irrigation water (CRWMS M&O 2000bo, Section 3.1.5.1). The affected farming community is presumed to be located approximately directly south of the potential repository in the Amargosa Valley. In the TSPA-SR, based on proposed regulations, the community (and the average member of the critical group) was assumed to be 20 km (12 mi) south of the repository. In the revised supplemental TSPA analyses, based on final regulations, the reasonably maximally exposed individual was assumed to be 18 km (11 mi) south. The receptor (average member of the critical group or reasonably maximally exposed individual) is an adult who lives at this location year round and uses a well as the primary source of water and otherwise has habits (e.g., consumption of locally produced foods) that are similar to those of the population of the Amargosa Valley. The contaminant transport pathways, routes taken by radionuclides through the biosphere from the source to a receptor, are typical for a farming community in this desert environment. Inhalation and direct exposure from surface contamination are intensified by the significant outdoor activity of a farming lifestyle. The exposure pathways (Figure 4-154) considered for the contaminated groundwater use scenario include consumption of tap water, locally produced leafy/root vegetables, fruits, grain, meat (beef and pork), poultry, milk and eggs, fish, inadvertent soil ingestion, inhalation of resuspended particulate matter, and external exposure to contaminated soil. Supplemental biosphere exposure pathway analyses for the groundwater use scenario consider a groundwater well at the location of the reasonably maximally exposed individual in the accessible environment (southernmost boundary of the controlled area) as the source of contamination. The reasonably maximally exposed individual is a hypothetical rural-resident receptor exposed to contamination through the same general exposure (transport) pathways as a farmer (as stated in the preamble of 40 CFR Part 197 [66 FR 32074, p. 32092]).

Since the biosphere modeling for the TSPA-SR model, some supporting documentation for the biosphere groundwater release exposure scenario has been revised, including updates of a limited number of parameter values. Discussion of the changes made to the biosphere model is contained in Volume 1, Section 13.4 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a). The most significant changes in the groundwater release exposure scenario are related to:

- Parameters defining employment and recreational behavior (duration of inhalation and external exposure times) (BSC 2001a, Section 13.2.1.4)
- Particulate concentrations in the air based on measurement of total suspended particles at Yucca Mountain and PM10 measurements from arid farming communities in the southwestern United States and the Yucca Mountain area (BSC 2001a, Section 13.2.1.4)
- Consumption rates of locally grown food for the critical group represented by distributions (BSC 2001a, Section 13.3.1)
- Parameters associated with the ingestion pathway for the current climate updated and new values developed for the cooler and wetter climate (glacial transition) (BSC 2001a, Section 13.2.1.5).

For the nominal scenario, the most significant contributing pathway to exposure is ingestion (CRWMS M&O 2001e, Section 6.7). The changes made based on the updated data had little impact on the nominal exposure ingestion pathway (BSC 2001b, Section 3.2.11.2).

The direct volcanic release scenario provides the framework for evaluating the radiological consequences of a volcanic eruption, wherein it is assumed that such an event would result in the deposition of radionuclide-contaminated ash on the soil surface. For the biosphere dose conversion factor calculations, the initial surface deposition of ash is assumed to remain on the soil surface rather than to become distributed (and thus diluted) throughout the surface soil layer. This approach maximizes the contribution to the inhalation pathway, considered the most important for direct volcanic releases. In addition, it accounts for the process of volcanic ash transfer from uncultivated areas (CRWMS M&O 2000bo, Section 3.1.5.2). Biosphere model supplemental analyses for volcanic release scenario confirm the importance of the inhalation pathway for this exposure scenario (BSC 2001a, Section 13.4.3).

The conditions for human exposure from volcanic ash deposition are the same as those considered for undisrupted performance. That is, the receptor is assumed to live year round in the farming community. The person is also assumed to be similarly involved in the activities typical of the current inhabitants of the region (e.g., has the same patterns of consumption of locally produced foods and similar periods of time spent in outdoor activities) (CRWMS M&O 2000bo, Section 3.1.5.2). Supplemental biosphere analyses indicate that the biosphere dose conversion factors for the average member of the critical group conservatively represent the reasonably maximally exposed individual (Williams 2001a, Section 5.2.5).

Updates in the biosphere model volcanic-eruption exposure scenario (radionuclides introduced to the biosphere by volcanic ash) since the TSPA-SR include revision of parameter values. A more detailed discussion of the changes made to the biosphere model is contained in Volume 1, Section 13.4 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a). The most significant changes include:

- Revision of parameters defining employment and recreational behavior (duration of inhalation and external exposure times) (BSC 2001a, Section 13.2.1.4)
- Revision to distribution of particulate concentrations in air for the volcanic scenario based on measurement from Mount St. Helens and Cerro Negro (BSC 2001a, Section 13.2.1.4)
- Development of new set of particle-resuspension factors for use after a volcanic event (BSC 2001a, Section 13.2.1.6)
- Development of distributions to represent consumption rates of locally grown food for the critical group (BSC 2001a, Section 13.3.1)
- Revision of parameters associated with the ingestion pathway for the current climate and develop values for the cooler and wetter climate (glacial transition) (BSC 2001a, Section 13.2.1.5).

Reevaluation of factors in the biosphere model volcanic-eruption exposure scenario (BSC 2001a, Section 13.4.3) results in changes to the expected annual doses. The particulate concentration in air was increased by a factor of 2.5. For the direct releases by volcanic eruption (ash fall), inhalation is the dominant pathway when integrated over time. (BSC 2001a, Section 13.3.6).

4.2.10.3.2 Mathematical Model

GENII-S, a computer program for statistical and deterministic simulations of radiation doses to humans from radionuclides in the environment (Leigh et al. 1993), was chosen to support the biosphere analyses for TSPA-SR. The program was found to be the most comprehensive code available for the analyses. GENII-S is flexible enough to address the FEPs applicable to Yucca Mountain, and it has been accepted by regulatory agencies for the purpose of environmental dose assessment. Furthermore, the program has the capability to sample over a range of environmental transport and human exposure parameter values for uncertainty and sensitivity analyses. Other criteria used in selecting GENII-S for use in the biosphere analyses are outlined in the *Biosphere Process Model Report* (CRWMS M&O 2000bo, Section 3.2.1.1).

Using a comprehensive set of environmental pathway models, GENII-S calculates the environmental transport of radionuclides following contamination of groundwater or contamination of soil resulting from the deposition of volcanic ash containing radionuclides. Based on the defined source term and exposure scenario, radionuclide transport through the biosphere as well as human internal and external exposure to key radionuclides are assessed. The entire process is an effort to describe the complex behavior of radionuclides in the environment and in humans using a mathematical abstraction, with the results of the modeling process being influenced by all uncertainties associated with the model itself, as well as with the model parameters (CRWMS M&O 2000bo, Sections 3.3.1 and 3.3.2). Uncertainty analyses summarized in Volume 1, Sections 13.2 and 13.3 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a) discuss the potential impact of fixed or single input values instead of distributions for parameters limited by the GENII-S calculation process, as well as the sensitivity of biosphere modeling to alternative receptor concepts. The many individual model components, including fixed parameter values or constraints on receptor parameters, contribute to the overall uncertainty. The analyses and multiple lines of evidence indicate that mathematical uncertainties contribute little additional uncertainty to the biosphere model (BSC 2001a, Section 13.2.2.2).

The principal results of the biosphere pathway analyses, biosphere dose conversion factors, are expressed as the radiation dose received from annual exposure to radionuclides in the environment for each unit of radioactivity concentration at the source of contamination. The dose conversion factors are then used in the TSPA-SR model and supplemental TSPA model analyses to estimate potential radiation dose based on the concentrations of a particular radionuclide at the source of that radionuclide (i.e., radioactivity per unit volume of well water for the contaminated groundwater use scenario, and activity per unit area of surface soil for the direct volcanic release scenario) (CRWMS M&O 2000a, Section 3.9; BSC 2001b, Section 2.2.2; Williams 2001a, Section 2; Williams 2001b, Section 2).

4.2.10.3.3 Biosphere Dose Conversion Factors for Contaminated Groundwater Use Scenario

For the contaminated groundwater use scenario, calculations of biosphere dose conversion factors were performed for radionuclides selected through an analysis designed to determine which radionuclides should be included in the TSPA-SR based on their expected contribution to the total potential dose (CRWMS M&O 2000dx). The groundwater contamination scenario is used to evaluate the radiological consequences of both undisturbed potential repository system performance and selected disruptive processes and events. The latter include the potential consequences of earthquakes and igneous intrusions, as well as consequences following a stylized human intrusion event (CRWMS M&O 2000bo, Section 3.1.5.1).

Radionuclide inventory was specified in terms of radionuclide concentrations in groundwater at the well head in units of pCi/L. The conversion factors, expressed as total effective dose equivalent from annual exposure (here also called annual dose) per unit activity concentration in groundwater, were calculated in units of mrem/yr per pCi/L. To incorporate the results of the calculations into the TSPA-SR predictive code in a computationally efficient manner, statistical distributions were fitted to the biosphere dose conversion factor data and distribution parameters were determined (CRWMS M&O 2000bo, Section 3.3.1.1). As noted before, a distribution of biosphere dose conversion factors represents the uncertainty due to the possible variabilities and uncertainties in the input parameters used (BSC 2001a, Section 13.4.1.2).

When contaminated groundwater is used to irrigate agricultural soil, the concentration of each contaminant in the soil will build up at a rate determined by the chemical properties and radioactive half-life of the material. Long-lived isotopes of elements that bind readily to soil particles may not reach an equilibrium concentration in soil for many hundreds of years, whereas relatively short-lived or mobile radioisotopes may approach their maximum concentrations in soil after only a few years of irrigation (CRWMS M&O 2000bo, Section 3.3.1.1).

To account for the radionuclide buildup in soil, biosphere dose conversion factors were calculated for each of six periods of cumulative years of irrigation with contaminated groundwater (CRWMS M&O 2000bo, Section 3.2.4.1.2, Table 3-6). With these calculations, it was possible to evaluate whether potential buildup of radioactivity in soil would change the estimated radiation doses received by the receptor. The irrigation time periods are the number of years that the land has been irrigated with contaminated groundwater before the point in time for which the biosphere dose conversion factors are calculated. The periods of previous irrigation are correlated with the period of time it takes until the equilibrium radionuclide concentration in soil is reached under the continuous irrigation conditions. The first of the six sets of biosphere dose conversion factors were always calculated under the assumption of no prior irrigation (i.e., radionuclide contamination in soils is absent). The remaining five irrigation periods were selected so that the biosphere dose conversion factors at each period would be approximately equally spaced between their no-prior-irrigation values and their long-term asymptotic (leveling off) contamination levels.

Table 4-30 outlines the biosphere dose conversion factors and soil buildup factors calculated for the contaminated groundwater use scenario and the distributions recommended by project scientists for use in the TSPA-SR analyses. Most of the conversion factors presented in Table 4-30 increased with the duration of previous irrigation (increasing time steps) (CRWMS M&O 2000bo, Section 3.3.1.1.1, Table 3-17), reflecting radionuclide buildup in soil. Supplemental biosphere dose conversion factor for supplemental TSPA model analyses are described in Volume 1, Section 13.4.1 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a) and *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Section 5.2.5). The radionuclide-specific conversion factors represent combined contributions from all pathways under consideration for a particular exposure scenario. Not every pathway component is influenced by the changing radionuclide concentration in soil. For example, the contributions to biosphere dose conversion factors due to ingestion of drinking water and the intake of the radionuclides that enter the food chain by deposition on plant surfaces during irrigation with contaminated water are insensitive to radionuclide buildup in soil. Examples of pathways that are sensitive to soil buildup include external exposure to radiation from contaminated soil, inhalation of resuspended soil particles, and radionuclide uptake by edible plants through their roots (CRWMS M&O 2000eq).

For most radionuclides, radionuclide buildup represented by the buildup factor was less than 15 percent (i.e., the soil buildup factor in Table 4-30 is less than 1.15). Because the estimated degree of buildup is not significant to the recommendation decision, for simplicity it was recommended that the biosphere dose conversion factor distributions appropriate to the longest periods of irrigation be used for these radionuclides (CRWMS M&O 2000bo, Section 3.3.1.1; CRWMS M&O 2000er, Section 7.1). These distributions

Table 4-30. Biosphere Dose Conversion Factor and Soil Buildup Factors for Radionuclides Introduced into the Biosphere through Irrigation with Contaminated Groundwater

Radionuclide	Biosphere Dose Conversion Factor		Soil Buildup Factor	Leveling Off Period (years)[a]
	Geometric Mean	Geometric Standard Deviation		
	mrem/yr per pCi/L			
Thorium-229	5.392	1.167	2.85	8,448
Cesium-137	0.1841	1.163	2.21	78
Strontium-90	0.1121	2.736	1.93	53
Americium-243	5.030	1.163	1.62	5,031
Uranium-232	2.064	1.150	1.13	93
Plutonium-239	4.976	1.151	1.10	1,456
Plutonium-240	4.953	1.151	1.10	1,456
Americium-241	5.012	1.156	1.08	1,117
Uranium-238	0.3512	1.159	1.04	93
Uranium-233	0.384	1.161	1.03	93
Uranium-234	0.3769	1.162	1.03	93
Uranium-236	0.3564	1.164	1.03	93
Technetium-99	0.001495	1.8423	1.01	5
Plutonium-238	4.109	1.161	1.01	227
Actinium-227	18.01	1.162	1.01	56
Neptunium-237	6.738	1.163	1.01	14
Iodine-129	0.3562	1.1874	1.00	5
Carbon-14	0.00055	1.5177	1.00	7,401

NOTES: [a]Approximate times required for biosphere dose conversion factor buildup to reach asymptotic value.
Sources: CRWMS M&O 2000a, Table 3.9-2; CRWMS M&O 2000bo, Table 3-19.

(one for each radionuclide) can be efficiently sampled by the TSPA computer code to generate the dose to the defined receptor from radionuclide contamination in the groundwater.

Of the four radionuclides that displayed greater than 15 percent increase due to soil buildup, thorium-229 showed the greatest degree of buildup, increasing by a factor of 2.85 relative to prior conditions (CRWMS M&O 2000bo, Table 3-19). For thorium-229 and americium-243, in the absence of soil loss, the time to approach the buildup limit was a few thousand years. As reported in a previous analysis (CRWMS M&O 2000eq, Section 7.2), soil loss has a significant effect on biosphere dose conversion factor buildup for these three radionuclides. The effect of soil erosion on cesium-137, strontium-90, and uranium-232 (with much shorter GENII-S buildup time) was much less pronounced due to their relatively short half-life.

The GENII-S program does not consider the mechanism of radionuclide removal by soil erosion. However, this issue was addressed in an analysis (CRWMS M&O 2000eo, Section 6.1) focusing on the major soils present in the Amargosa Valley area near the proposed location of the receptor. These annual soil loss estimates were incorporated into the overall modeling calculations to account for radionuclide removal from the 15-cm (6-in.) surface soil layer. The rate of soil removal by erosion under natural conditions is generally in approximate equilibrium with the rate of soil formation from the transformation of underlying bedrock, alluvium, colluvium, or other geologic material comprising the parent material. Under these conditions, the soil depth (or thickness) is maintained at a near constant depth through time (Troeh et al. 1980, p. 4). Human activities, including tilling of cropland, removal of vegetation, and grazing of pasture or rangeland, typically tend to accelerate the natural rate of soil removal. Disturbed soil is generally left with less protection against the action of water and wind. Thus, the formation of new soil cannot keep pace with the accelerated erosion rate, and the soil material may progressively become thinner (Troeh et al. 1980, pp. 5 and 6). The annual rate of soil loss for the major soil series in the vicinity of the proposed receptor generally was estimated to be between 0.06 and 0.08 cm/yr (0.024 to 0.031 in./yr) (CRWMS M&O 2000eo, Section 6.1.1).

The degree of buildup for thorium-229 and americium-243, once soil loss was considered, was sufficiently small (less than 20 percent) that there was little benefit of incorporating a probabilistic sampling for the time of previous irrigation. Thus, for simplicity, the asymptotic (i.e., long time irrigation buildup period) biosphere dose conversion factor mean was used. Although americium-243, thorium-229, and uranium-232 are predicted to have more significant buildup in soil, these radionuclides have not been significant contributors to dose in previous TSPA evaluations. For thorium-229 and americium-243, the periods needed for maximum buildup are 8,448 and 5,031 years, respectively, and continuous farming activity on a single plot of irrigated land over such extended periods of time is unlikely (CRWMS M&O 2000bo, Section 3.3.1.1). Comparing the mean values of biosphere dose conversion factors for the nominal scenario used in the TSPA-SR model (given in CRWMS M&O 2000er, Table 3) with the new data (CRWMS M&O 2001f, Section 7.2) indicates the small net effect of the change in biosphere dose conversion factors. The TSPA-SR model identified the radionuclides contributing most to annual dose as technetium-99, iodine-129, neptunium-237, and plutonium-239 (CRWMS M&O 2000a, Figure 4.1-6). As an indication of the relative differences for technetium-99, iodine-129, and neptunium-237, the revised biosphere dose conversion factor values are lower by no more than 20 percent than those used in TSPA-SR. The change for plutonium-239 in the biosphere dose conversion factor is less than 20 percent (BSC 2001b, Section 3.2.11.2).

The relatively small effect of updates to the biosphere model on the expected annual dose for the nominal scenario is reflected in the supplemental TSPA model results (BSC 2001b, Figure 3.2.11-1a). The mean annual dose using the updated uncertainty distributions for the biosphere dose conversion factors (BSC 2001a, Section 13.4.) is compared to the results calculated in the TSPA-SR model in Volume 2, Figure 3.2.11-1a of *FY01 Supplemental Science and Performance*

Analyses (BSC 2001b). The differences between the previously calculated annual dose (TSPA-SR base-case results) and the supplemental TSPA model results (of less than 10 percent in simulated annual dose for most times) do not constitute a large change (BSC 2001b, Section 3.2.11.2). Supplemental biosphere dose conversion factors for supplemental TSPA model and revised supplemental model analyses are described in Volume 1, Section 13.4.1 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a) and *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Section 5.2.5).

4.2.10.3.4 Biosphere Dose Conversion Factors for Direct Volcanic Release Scenario

The biosphere model for a direct volcanic release (volcanic eruption) considers both inhalation of contaminated ash during the eruption and radionuclide transport and uptake following the deposition of contaminated volcanic ash (CRWMS M&O 2000bo, Section 3.1.5.2). Human exposure may occur as a result of inhalation of fine particles of contaminated ash during the eruptive event, inhalation of resuspended ash after deposition, ingestion of larger particulates after inhalation both during and after the event, and ingestion of contaminated crops and animal products. Consumption of contaminated water, which is an important pathway for the nominal scenario, is not included as a pathway for the direct volcanic release scenario because there is no significant quantity of surface water in the Yucca Mountain region that might be contaminated by volcanic ash.

Ash concentrations in the air may be extremely high during the eruptive event, and humans who do not leave the region may be exposed to radiation by both inhalation and ingestion of particulates. Dose factors that account for inhalation of fine and coarse particulates were developed for an eruptive event duration spanning between 33 minutes and 73 days. Analysis of potential doses as a result of inhalation during the eruption shows that it is a minor contributor to total probability-weighted dose from volcanic eruption because of the relatively brief duration of the event compared to the long-term exposure that could occur from ash after it is deposited (CRWMS M&O 2000a, Section 5.2.9.9). The TSPA analyses of doses from direct volcanic releases were therefore focused on consideration of exposures incurred after contaminated ash is deposited. Detailed description of the processes and assumptions considered for the modeling of the scenario are in Section 3.10.3.1 of *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a).

Biosphere dose conversion factors developed for the direct volcanic release scenario are outlined in Table 4-31. Seventeen radionuclides were identified as relevant for calculation of biosphere dose conversion factors under a volcanic (igneous activity) event contamination scenario (CRWMS M&O 2000a, Section 3.10.3.5, Table 3.10-8; CRWMS M&O 2000bo):

- Strontium-90
- Cesium-137
- Lead-210
- Radium-226
- Actinium-227
- Thorium-229
- Thorium-230
- Protactinium-231
- Uranium-232
- Uranium-233
- Uranium-234
- Plutonium-238
- Plutonium-239
- Plutonium-240
- Plutonium-242
- Americium-241
- Americium-243.

The list of radionuclides of interest is somewhat different than that considered for the contaminated groundwater use scenario because it reflects the radionuclide inventory directly released from the repository during a volcanic eruption, as opposed to radionuclides transported to the biosphere by groundwater in the saturated zone, where substantial retardation and sequestering of many radionuclides may occur within the geologic strata.

Table 4-31. Statistical Output for Direct Volcanic Release Scenario Biosphere Dose Conversion Factors for the TSPA-SR

Radionuclide	Biosphere Dose Conversion Factors (rem/yr per pCi/m²) Arithmetic Mean	Arithmetic Standard Deviation
Strontium-90	1.22×10^{-8}	1.91×10^{-8}
Cesium-137	1.28×10^{-9}	1.52×10^{-9}
Lead-210	6.05×10^{-8}	6.68×10^{-8}
Radium-226	5.66×10^{-9}	3.42×10^{-9}
Actinium-227	7.34×10^{-7}	6.46×10^{-7}
Thorium-229	2.31×10^{-7}	2.06×10^{-7}
Thorium-230	3.47×10^{-8}	3.09×10^{-8}
Protactinium-231	1.63×10^{-7}	1.24×10^{-7}
Uranium-232	7.39×10^{-8}	6.45×10^{-8}
Uranium-233	1.50×10^{-8}	1.30×10^{-8}
Uranium-234	1.48×10^{-8}	1.28×10^{-8}
Plutonium-238	4.94×10^{-8}	3.78×10^{-8}
Plutonium-239	5.48×10^{-8}	4.19×10^{-8}
Plutonium-240	5.47×10^{-8}	4.19×10^{-8}
Plutonium-242	5.11×10^{-8}	3.91×10^{-8}
Americium-241	5.60×10^{-8}	4.27×10^{-8}
Americium-243	5.59×10^{-8}	4.26×10^{-8}

Source: CRWMS M&O 2000a, Table 3.10-8.

Revised volcanic eruption scenario biosphere dose conversion factors are developed for evaluation of transition and steady-state phases of a potential eruption. Mass loading is the most important biosphere model parameter distinguishing the different phases of the scenario. The impact of mass loading and the development of updated biosphere dose conversion factors is described in Volume 1, Section 13.4.3 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a). Table 13.4-10 in Volume 1 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a) summarizes the updated biosphere dose conversion factors for the volcanic eruption scenario.

The receptor of interest for the direct volcanic release scenario was the same as used in the nominal groundwater release scenario. Radionuclide inventory was specified in terms of basic concentrations that exist after transport of volcanic ash has occurred. The inventory activity concentration units selected (pCi for activity and m² for soil inventory) resulted in basic concentrations in surface soil in the units of pCi/m². Biosphere dose conversion factors expressed as annual total effective dose equivalent per unit activity deposition, per unit area, were calculated in units of rem/yr per pCi/m².

As with the case of biosphere dose conversion factors for the contaminated groundwater use scenario, calculations of conversion factors for the direct volcanic release scenario were performed in a series of probabilistic runs to propagate the uncertainties of input parameters into the output. A Latin Hypercube sampling method (a form of stratified Monte Carlo sampling) was used in the stochastic (probabilistic) analysis with the number of realizations set to 160, which was the maximum that the software could perform due to its computing limitation. However, it was determined that this number of realizations was sufficient to obtain statistically valid results (CRWMS M&O 2000bo, Section 3.3.2).

Input values were reflective of the air quality conditions (increased dustiness) following volcanic eruption (CRWMS M&O 2000bo, Section 3.3.2.2). Specifically, probability distribution functions of total suspended particulates in air and of the respirable fraction of suspended particulates were developed based on the documented air quality data from volcanic eruptions, such as Mount St. Helens and Montserrat. These data were also used to develop other GENII-S parameters whose values were affected by the conditions of increased particulate concentration in air, such as the crop resuspension factor and the inadvertent soil ingestion.

Similar to the case of groundwater contamination, the effects of surface soil removal by erosion were included in the evaluation of the expected annual dose to the receptor from volcanic eruption (CRWMS M&O 2000a, Section 3.10.3.2).

Reevaluation of factors influencing the biosphere dose conversion factors for the volcanic eruption scenario (BSC 2001a, Section 13.4.3) results in updated uncertainty distributions of biosphere dose conversion factors. The particulate concentration in air increased by a factor of 2.5 (BSC 2001a, Section 13.3.6), resulting in an increase in biosphere dose conversion factors that propagates through to potentially significant changes to the predicted dose. Biosphere dose conversion factors are developed for three phases (eruption, transition, and steady-state) during and following the assumed volcanic eruption. The biosphere dose conversion factor distributions for the transition phase (BSC 2001a, Section 13.4.3) are the more conservative values used in supplemental TSPA model calculations. The biosphere dose conversion factors that are applicable for the eruption phase are not used in TSPA analyses because of the short duration of the eruptive phase. The transition phase biosphere dose conversion factors are conservative relative to the biosphere dose conversion factors for the steady-state phase following eruption because the volcanic ash is more available for resuspension in air during the transition phase. The case with the highest biosphere dose conversion factors (i.e., the 1-cm [0.4-in.] thick ash layer with annual average airborne particulate concentration) is used for supplemental TSPA model analyses (BSC 2001b, Section 3.2.11.2). The expected mean annual dose using the updated uncertainty distributions for the volcanic eruption biosphere dose conversion factors compared to the results calculated in TSPA-SR is approximately 2.5 times greater. This represents a significant increase relative to previous results and is primarily due to the increase in the respirable fraction of particulate concentration in air within the biosphere model (BSC 2001a, Section 13.3.6.2). However, the higher expected annual dose from direct exposure to contaminated volcanic ash using the updated volcanic eruption biosphere dose conversion factors is still lower than the expected annual dose from the igneous groundwater pathway at later times (compare to Figure 4.2-1 of *Total System Performance Assessment for the Site Recommendation* [CRWMS M&O 2000a]).

4.2.10.3.5 Limitations and Uncertainties

A review of the list of FEPs applicable to the Yucca Mountain Project identified primary FEPs that were potentially applicable to the biosphere (CRWMS M&O 2000bo, Section 3.1.3). Each of these primary FEPs was screened to determine if it was applicable to Yucca Mountain considering the proposed NRC regulations (10 CFR Part 63 [64 FR 8640]) and the local environment. The results of this screening process are outlined in Appendix B of the *Biosphere Process Model Report* (CRWMS M&O 2000bo). Additional screening of biosphere FEPs, consistent with EPA and NRC rules, is discussed in *Evaluation of the Applicability of Biosphere-Related Features, Events, and Processes (FEPs)* (BSC 2001t, Section 6.1). Those FEPs which were screened out as not applicable to Yucca Mountain included either (1) issues precluded from consideration by the proposed NRC regulations (e.g., social and institutional development, technical development, species evolution) or (2) FEPs that were deemed unlikely to occur in the Yucca Mountain biosphere (e.g., capillary rise of water from the saturated zone to the repository, marine features).

As with any modeling effort, uncertainty is inherent in the biosphere model (CRWMS M&O 2000bo, Sections 3.3.1.2 and 3.3.2.2). This means that modeling results carry uncertainty resulting from both uncertainties in the model itself and uncertainties in model parameters. Uncertainty and sensitivity analyses were used to assist in interpreting the results of analysis. The probabilistic approach was used for both sensitivity and uncertainty analyses. The objective of sensitivity analysis was to determine which parameters affect the model results the most, whereas the objective of uncertainty analysis was to determine how the uncertainty in model parameters affects the model results.

Uncertainty analysis shows quantitatively the effect of propagation of input parameter uncertainties on the resulting biosphere dose conversion factors. Uncertainty in the modeling results includes contribution from both the model and the parameter uncertainty. Uncertainty analysis for the conversion factors was focused on the parameter uncertainty, which represents uncertainty in the data, parameters, and coefficients used in mathematical models and the supporting computer program, GENII-S. Parameter uncertainty originates from a number of sources including uncertainty in determining parameter and coefficient values used in the biosphere model, and uncertainty associated with the temporal and spatial heterogeneity of the biosphere system.

Contribution of parameter uncertainty to the overall uncertainty of the modeling outcome can be more readily quantified than model uncertainty. In the case of the biosphere modeling, the probabilistic approach was taken which allows statistical sampling of parameter values described by their probability distribution functions.

Because the biosphere environment is complex in nature, any representation of the contaminant transport pathways is a simplified version of the reality on which it is based. For the TSPA-SR, some input parameters were obtained through field measurements and the regional survey, while others were derived from existing literature. The parameters used in the biosphere analyses can be classified into two main categories: (1) parameters that influence, or are related to, the transport and accumulation of radionuclides in the biosphere; and (2) parameters related to characteristics of the receptor (i.e., consumption patterns, lifestyle characteristics, and land use). Each parameter value or range of values used represented either a reasonable or conservative estimate regarding potential contribution to the total dose to the receptor. The GENII-S computer code allows the representation of certain input parameters as variable in nature (probability distributions), while others may only be represented as fixed values. The parameters selected for use in the biosphere analyses are described in detail in the *Biosphere Process Model Report* (CRWMS M&O 2000bo, Section 3.2.4).

In the TSPA-SR biosphere analyses, the assessment philosophy is to use generally conservative assumptions to ensure that the results are unlikely to underestimate the corresponding values of dose conversion factors for the radionuclide transport and uptake conditions and mechanisms considered. For example, it is conservatively assumed that all (100 percent) of the water used or consumed in the biosphere is contaminated. This assumption applies to several aspects of the total biosphere model, including parameters that describe:

- Drinking water for human consumption
- Water for beef cattle and dairy cow consumption
- Water for poultry and laying hen consumption
- Irrigation water for terrestrial food production (leafy and root vegetables, fruit, and grain for human consumption)
- Irrigation water for production of fresh and stored feed for animals used directly or indirectly as food sources.

A thorough discussion on the various GENII-S input parameters and the degree of conservatism assumed for these parameters are in Section 3.2.4 of the *Biosphere Process Model Report* (CRWMS M&O 2000bo).

Limitations to the biosphere pathway analyses are generally associated with the uncertainty within the mathematical representation of the conceptual model and the input parameters used in the analyses. Input parameters were quantified using site specific data and other accepted information (e.g., government publications, and journal articles and reports). Validation of the biosphere process concluded that the combination of the conceptual model, appropriately selected input parameters, and the mathematical expressions of the processes involved are valid for use in evaluating the Yucca Mountain biosphere (CRWMS M&O 2000bo, Section 5.2).

Sensitivity and pathway analyses were conducted for the biosphere dose conversion factors calculated for both the contaminated groundwater irrigation scenario and the disruptive event scenario. The purpose of these analyses was to determine which pathways and input parameters have the greatest influence on the biosphere dose conversion factors. Uncertainty analysis shows quantitatively the effect of propagation of input parameter uncertainties on the calculated conversion factors. Information on pathway sensitivity, input parameter sensitivity, and biosphere dose conversion factor uncertainty provides a context for the estimates of biosphere dose conversion factors while focusing attention and resources on parameters and modeling decisions that could have the greatest influence on the calculations for the various scenarios (CRWMS M&O 2000es). Details on the methodology used to conduct the sensitivity and uncertainty analyses are provided in Sections 3.3.1.2 and 3.3.2.2 of the *Biosphere Process Model Report* (CRWMS M&O 2000bo).

Additional analyses discussed in Volume 1, Section 13.3 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a) provides a better understanding of various uncertainties and sensitivities inherent in the biosphere model. Of special interest to the biosphere model is the sensitivity of the mathematical code to alternative receptor concepts (details of dietary and lifestyle definition). The receptor in the biosphere model is evaluated as a source of uncertainty by varying the dietary characteristics. Uncertainty due to the receptor is likely to be bounded by the biosphere dose conversion factors used in the TSPA-SR model (BSC 2001a Section 13.3.1.8). Other uncertainties evaluated included the effect of the partition coefficients on biosphere dose conversion factors, the impact of fixed ingestion pathway parameters inputs within GENII-S, and water-usage in future cooler, wetter climates. GENII-S treats radionuclide accumulation in and depletion from the surface soil. The depletion (leaching and removal by decay or plant uptake) is subject to uncertainty of a fixed input parameter (partition coefficient of the element). For certain radionuclides, a large change in the assumed coefficient causes an insignificant change (few tens of percent) while changes for other radionuclides are more significant (increase by a factor of five). The net effect can be approximated resulting in an increased spread in the distribution in the biosphere dose conversion factors representing increased total uncertainty in the biosphere model if applied (BSC 2001a, Section 13.3.3). Additional uncertainty due to fixed ingestion pathway parameters can be approximated with large estimated uncertainties noted for important radionuclides (BSC 2001a, Section 13.3.4). The water-usage uncertainty analysis predicted a decrease for the cooler, wetter (future glacial-transition) climate (BSC 2001a, Section 13.3.5). The overall uncertainty associated with the mathematical model is not quantified; however, the multiple lines of evidence indicate that the mathematical uncertainties contribute little additional model uncertainty (BSC 2001a, Section 13.2.2).

For the contaminated groundwater use scenario, the inhalation and external exposure pathways are not significant, and the ingestion pathway accounts for essentially all of the biosphere dose conversion factor. The most important parameters for all radionuclides of interest, except carbon-14 and cesium-137, are ingestion of drinking water, followed by ingestion of leafy vegetables. Consumption of fish, assumed to be raised in large, man-made containers filled from groundwater sources, is the greatest contributor (more than 90 percent) of carbon-14. Fish consumption is the leading contributor to the conversion factor for cesium-137, followed by drinking water, leafy vegetables, and meat. Additional pathway exposure analysis confirms the importance of the ingestion pathway within the biosphere dose conversion factors (BSC 2001a, Section 13.4.1.4).

4.2.10.3.6 Alternative Conceptual Processes

As stated previously, no alternative conceptual models were developed for the overall biosphere modeling process consistent with the licensing-related regulatory framework (CRWMS M&O 2000bo, Section 3.5). In addition, review of publicly available documents produced by the DOE and external agencies and organizations indicates that there are no alternative conceptual processes or major opposing views to the overall biosphere analysis process consistent with the regulatory framework. The main reason for the absence of opposing views regarding alternative conceptual models is that the strategy for conceptualizing the biosphere pathway analyses is consistent with similar activities being pursued by the international scientific community (BIOMOVS II Steering Committee 1994; BIOMOVS II 1996; National Research Council 1995). Furthermore, the biosphere analyses have been based on the reference biosphere consistent with the licensing-related regulations (10 CFR Part 63 [66 FR 55732]). This limits the biosphere system being studied/modeled as well as alternative locations for the reasonably maximally exposed individual or future population and socioeconomic considerations.

4.2.10.3.7 Model Calibration and Validation

Model validation is a process used to establish confidence that a conceptual model represented in a mathematical model, by software, or by other analytical means, adequately represents the phenomenon, process, or system under consideration. In the case of the biosphere pathway analyses for the potential repository at Yucca Mountain, complete validation of the model is not feasible because direct observation of the actual outcome will not be possible for many years to come, if ever. However, an independent technical review of the model was commissioned to enhance confidence in the biosphere conceptual model (CRWMS M&O 2000bo, Section 3.2.3). A variety of reports with a similar scope were evaluated, and it was determined that the biosphere model developed does reasonably reflect the environmental conditions in the Amargosa Valley. The review also concluded that the methods, references, and data sources used by the analysts were sound and that the GENII-S input values were reasonable for the environment conditions of the biosphere pathway analyses (CRWMS M&O 2000bo, Section 3.2.3).

The GENII-S code was also subjected to the DOE software qualification process (CRWMS M&O 1998k). The qualification process makes use of test cases supplied by the software developer to verify that the software, as installed on project computers, produces outputs that are consistent with values expected for a prescribed set of inputs. Additionally, a special test case tailored to exercise all the GENII-S pathways and features relevant to Yucca Mountain analyses was developed. The expected results of the analysis were calculated by hand using the equations from the GENII-S mathematical model. Agreement of the GENII-S results and hand calculations were found to be within ±5 percent, and the code was subsequently designated as qualified software. Finally, an analysis was conducted to evaluate the reconciliation of the biosphere dose conversion factors for the Yucca Mountain case with other dose calculations obtained by the GENII-S and GENII (the predecessor code to the GENII-S code). Project scientists identified several recent applications of the codes that provided a basis for comparison of the predicted dose to a receptor as a consequence of exposure to radioactive contaminants in surface soil and groundwater. The annual total effective dose equivalent from unit concentrations of various radionuclides in groundwater and soil was then inferred from the different calculations and compared to the dose conversion factors for the Yucca Mountain case. This comparative analysis showed that the calculated Yucca Mountain biosphere dose conversion factors were largely consistent with the estimated dose per unit activity concentrations in groundwater and soil, once the effects of the different input parameter values and settings associated with the various applications were taken into account.

4.2.10.4 Total System Performance Assessment Abstraction

4.2.10.4.1 Contaminated Groundwater Use Scenario

To obtain annual radiation dose (mrem/yr) to the receptor (the reasonably maximally exposed individual in supplemental and revised supplemental TSPA analyses), the biosphere dose conversion factor (mrem/yr per pCi/L) for each radionuclide calculated in the biosphere pathway analyses was multiplied by its corresponding concentration (pCi/L) in the groundwater at the accessible environment.

The steps that occur within the TSPA model to calculate annual dose are as follows. Radionuclide amounts in groundwater are specified in terms of mass flux (specified in units of grams per year [g/yr]) which, when multiplied by the activity for the particular radionuclide (in units of curies per gram [Ci/g]), is converted to an activity flux. When divided by the water-usage volume of the hypothetical farming community (specified in units of liters per year [L/yr]), the activity flux is converted to an activity concentration, specified in units of picocuries per liter (pCi/L). The biosphere dose conversion factors, expressed as annual dose per unit activity concentration in groundwater, are calculated in units of mrem/yr per pCi/L. Thus, the radionuclide concentration in the water-usage volume is multiplied by the appropriate biosphere dose conversion factor to determine the annual dose (in units of rem/yr). The annual dose is therefore the sum of the products of the biosphere dose conversion factors for each radionuclide and the radioactivity available for each radionuclide from agricultural and domestic processes, based upon the groundwater concentrations.

4.2.10.4.2 Direct Volcanic Release Scenario

In the case of the direct volcanic release scenario, volcanic ash contaminated with radionuclides is assumed to be dispersed in the air and eventually settles to the ground, thereby contaminating the agricultural soils in the reference farming community. The biosphere exposure scenario involves individuals exposed to contaminated ash during and following volcanic eruption. Biosphere dose conversion factors for the volcanic eruption are expressed in units of rem/yr per pCi/m^2.

Within the TSPA model, the areal mass of a radionuclide in the ash deposited on the ground surface is calculated, considering radioactive decay and soil removal. The areal mass is then converted to areal activity, and the areal activity is multiplied by the appropriate biosphere dose conversion factor to realize the annual total effective dose equivalent for that radionuclide. Within the model, at every time step, the annual doses for all the radionuclides are summed to determine the total annual dose. Doses are calculated separately for the volcanic eruptive release mechanism, igneous intrusion groundwater release mechanism, and the nominal scenario. These doses are subsequently combined to obtain the expected annual dose to the receptor.

The probability-weighted dose attributed to the direct volcanic release scenario is combined with the dose attributed to contaminated groundwater use (nominal scenario) to calculate the total system dose to the receptor of interest.

For the overall TSPA-SR analyses and supplemental TSPA model, uncertainties in the biosphere modeling input parameters were carried forward in the TSPA calculations by sampling from the full distribution for the biosphere dose conversion factors developed by the biosphere process model.

4.3 SCENARIOS OF FUTURE CONDITIONS THAT COULD AFFECT REPOSITORY PERFORMANCE

The TSPA examines a range of possible future conditions (i.e., features, events, and/or processes) that could affect the repository's long-term performance. The TSPA considers a range of possible future conditions because it is not possible to forecast future conditions precisely. The uncertainty in future conditions is due to a combination of limited information about the FEPs that could affect repository performance and the inherent variability or randomness in natural processes. In principle, more information can be gained through further testing and analysis. However, complete knowledge is unattainable because investigations of site features must sample limited parts of the site, and monitoring of events and investigations of long-term processes must be conducted over limited periods of time.

The condition identification and screening process that is described below ensure that potentially relevant FEPs are considered in the TSPA. The amount of uncertainty associated with each feature, event, or process will vary. However, one of the key advantages of TSPA as an analytical and decision-aiding tool is that it provides a structured framework for expressing and evaluating the significance of uncertainties in future conditions. The structured screening process and the TSPA ensure that the range of possible future conditions are factored explicitly into the projections of repository performance. The uncertainty in inputs to the TSPA results in a range of possible future outcomes (i.e., a range of possible future doses to the receptor group). Probabilities assigned to the various TSPA inputs are carried through the analysis so that the range of potential doses is defined by a probability distribution. The mean dose can then be calculated from the probability distribution.

The TSPA approach followed here uses scenarios to evaluate the significance of uncertainty in the future system conditions and to assess its impact on projected exposures. Scenarios are combinations of possible future conditions and are grouped into two general categories: (1) a nominal scenario and

(2) disruptive scenarios. The nominal scenario includes the most likely conditions that could occur in the future (e.g., climate change, seismic activity, or repository heating). The disruptive scenario category includes conditions that are very unlikely (e.g., nuclear criticality, or water table rise) but that could, if they were to happen, adversely impact the capability of the repository system to isolate radioactive waste.

As noted in Section 4.1.1.2, the DOE has initiated several activities to improve the treatment of uncertainty in current models. Additionally, as noted in Section 4.1.4, the DOE has evaluated the possibility of mitigating uncertainties in modeling long-term repository performance by operating the design described in this report at lower temperatures. The nominal scenario (particularly with respect to repository heating) and the disruptive scenarios described above have been reevaluated and documented in *Yucca Mountain Preliminary Site Suitability Evaluation* (DOE 2001b).

The following sections provide additional information and background on how the DOE arrived at the scenarios that were analyzed for this report. Specifically, the subsequent sections focus on:

- Outlining the systematic methodology used to select the scenarios analyzed to evaluate repository system performance
- Describing the characteristics of the nominal, disruptive, and human intrusion scenarios considered in the TSPA
- Explaining the basis for the exclusion of certain scenarios historically debated by scientists.

More detailed technical information on future system conditions and scenarios can be found in the *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a), *FY01 Supplemental Science and Performance Analyses* (BSC 2001a; BSC 2001b), *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a), *The Development of Information Catalogued in REV00 of the YMP FEP Database* (Freeze et al. 2001), and a series of analysis model reports on FEPs (e.g., BSC 2001t; CRWMS M&O 2000cx, 2000ef, 2000et, 2000eu, 2000ev, 2000ew, 2000ex).

4.3.1 Methodology for Developing Scenarios

The method used to develop the nominal and disruptive scenarios is summarized on Figure 4-156 and in the following five sections. A more detailed explanation of the scenario development methodology can be found in *Total System Performance Assessment—Site Recommendation Methods and Assumptions* (CRWMS M&O 2000ey).

As used in this report, a scenario is defined as a combination of FEPs. In the specific context of scenarios, features are physical, chemical, thermal, or temporal characteristics of the site or repository system. Examples of features are fracture systems or faults. Processes are typically phenomena and activities that have gradual, continuous interactions with the repository system or subsystem. Percolation of meteoric water into the unsaturated rock layers above the potential repository is an example of a process. Events and processes can be interrelated, but in general, events are discrete occurrences for which probability and consequence can be assessed. Volcanism, for example is an event that is relevant to disruptive scenarios.

Step 1: Identify and Classify Potentially Relevant Conditions—The DOE assembled an initial list of possible future conditions (i.e., FEPs) that could affect the repository system using a draft list in the Nuclear Energy Agency's working group database (NEA 1999b). Scientists working on nuclear waste programs in several countries compiled this comprehensive database as a collaborative effort. They identified generic future conditions using a variety of methods, which included informal expert elicitation, judgments of subject matter experts, logic tree analyses, stakeholder reviews, and regulatory criteria. The Nuclear Energy Agency database, which currently contains more than 1,200 entries for future conditions, was constructed using input from scientists

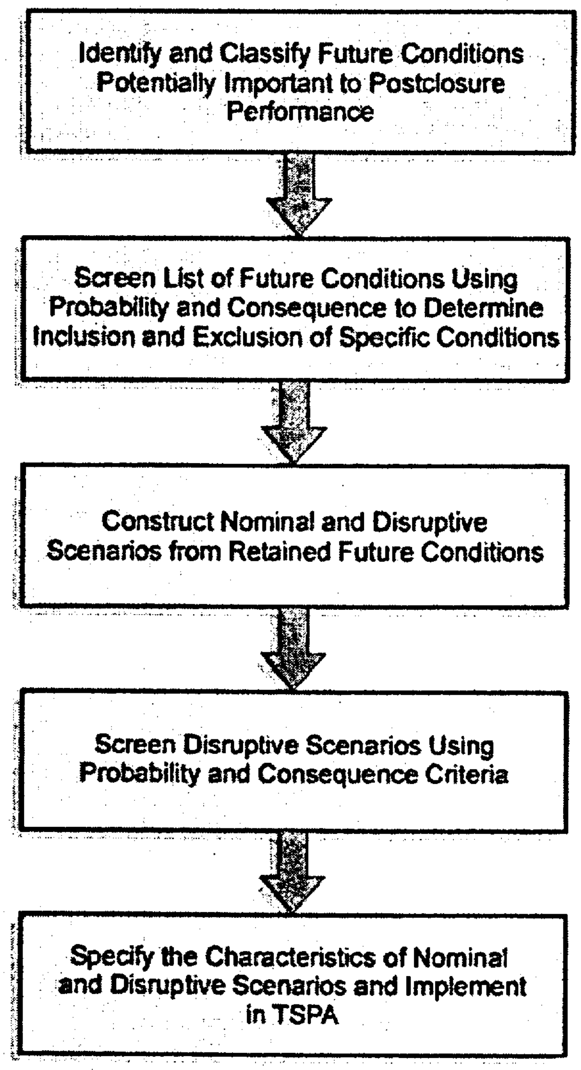


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Figure 4-156. Major Steps In Scenario Selection Methodology

affiliated with the U.S. Waste Isolation Pilot Plant program; Canadian, Swiss, and Swedish spent nuclear fuel programs; and the intermediate- and low-level waste programs of the United Kingdom.

The DOE expanded the initial list of potential future conditions by adding site-specific FEPs identified in previous Yucca Mountain performance assessment studies (Ross 1987; Wilson, M.L. et al. 1994, Section 3.2; CRWMS M&O 1995, Section 2.7). These additional future conditions represent the specific and unique geologic and hydrologic characteristics of the Yucca Mountain region. They also reflect future conditions that could affect the repository facility, waste package, and other engineered barriers.

The DOE developed an electronic database with over 1,700 entries from the Nuclear Energy Agency and DOE lists of potential future conditions. The entries in the DOE database were classified using the Nuclear Energy Agency's classification method. The DOE streamlined the database by combining similar entries and organizing them into primary and secondary categories. The primary entries, which collectively form a site-specific list of future conditions, then went into the scenario methodology. The entries that were redundant or that otherwise could be appropriately combined into a single representation of a future condition were placed in a secondary category. The rationale for primary and secondary categorizations is described in the DOE's database (Freeze et al. 2001). Eleven additional FEPs were added to the list in 2001 (Freeze et al. 2001).

Step 2: Screen the List of Future Conditions—The next step in the scenario methodology, shown in detail in Figure 4-157, involved refining the list by excluding future conditions due to low probability or consequence consistent with NRC licensing-related regulations (see 10 CFR 63.114(c) and (d) [66 FR 55732]). These criteria establish the technical basis for excluding FEPs from further analysis.

The first reason involves the probability of the event occurring (10 CFR 63.114(d) [66 FR 55732]). The TSPA considers events that have at least 1 chance in 10,000 of occurring in 10,000 years. Therefore, any event with an estimated probability of occurrence less than 10^{-4} in 10^4 years was excluded from further consideration in the TSPA. For example, an impact by a meteorite is a low-probability event not considered in the TSPA because the estimated probability for this event is about 10^{-12} per year (Ross 1987, p. 42).

The second reason addresses the significance of the radiological consequences of potential future conditions. The DOE did not consider, in detail, potential future FEPs with low consequences. For example, surface processes that are certain to occur, such as erosion and sedimentation, have no significant impact on a repository's capability to meet the radiation protection standard and were, therefore, excluded from consideration in the TSPA.

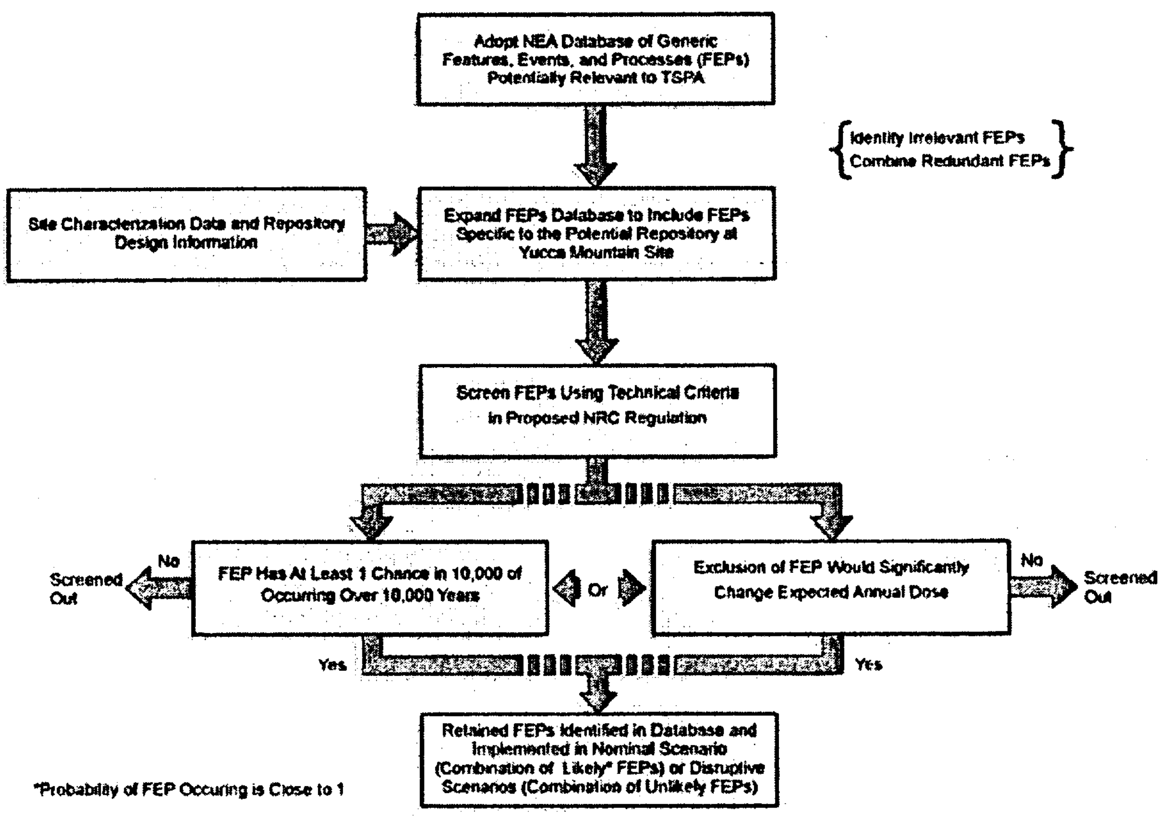

Figure 4-157. Schematic Illustration of the Screening Process
NEA = Nuclear Energy Agency.

Step 3: Construct Nominal and Disruptive Scenarios—The nominal scenario was constructed using all expected conditions (i.e., future conditions that are very likely to operate after closure) that were retained after screening. Stated simply, the nominal scenario represents the most plausible evolution of the geologic repository system and includes both favorable and adverse (e.g., seismicity) future conditions. Similarly, disruptive scenarios were developed using combinations of the adverse future conditions. These disruptive scenarios represent low-probability (but greater than the screening probability) perturbations to the expected evolution of the geologic repository system. To a limited extent, logic diagrams (Cranwell et al. 1990), which are mathematically equivalent to the NRC "Latin square" approach (NRC 2000c, Section 4.4.2), have also been used. Both approaches provided a systematic and transparent method for establishing all possible combinations of disruptive conditions and for calculating the probabilities of those combinations (Wescott et al. 1995, Chapter 3). In addition, the logic diagrams were used to establish the empirical probability for the nominal scenario (i.e., computed by taking one minus the sum of the disruptive scenario probabilities).

Step 4: Screen Scenarios—Analysts further refined the specification of the nominal scenario and screened the initial set of disruptive scenarios. The screening of the disruptive scenarios was performed using probability and consequence discussed in the previous screening step. As a result of this screening, a number of scenarios associated with faulting, nuclear criticality (within 10,000 years following emplacement), and water table rise were eliminated from consideration. In addition, the scenarios were reviewed by groups of subject matter experts to ensure that the uncertainties in future conditions were properly represented.

Step 5: Implement Scenarios for Total System Performance Assessment—Collectively, the nominal scenario and selected disruptive scenario (i.e., igneous activity) effectively specify the range of possible future events and processes that could affect the repository's capability to provide long-term isolation of the radioactive waste. The TSPA evaluates each scenario separately to account for the uncertainties in models and parameters. TSPA calculations for the individual scenarios and the overall evaluation are summarized in Section 4.4 and documented in more detail in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a). Additional calculations are documented in *FY01 Supplemental Science and Performance Analyses* (BSC 2001a; BSC 2001b). Further supplemental calculations are documented in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a).

4.3.2 Scenarios Considered in Total System Performance Assessment

The potential repository's capability to isolate radioactive waste is evaluated by modeling scenarios of the evolution of the geologic system and the occurrence of unlikely adverse conditions. Using the systematic procedure described in Section 4.3.1, earth scientists and engineers have developed scenarios of future system evolution and unlikely adverse conditions. These scenarios, which were developed by combining FEPs relevant to the site, are grouped into two basic categories: a nominal scenario and disruptive scenarios.

The nominal scenario includes the most likely FEPs expected to occur in the future (e.g., climate change, repository heating). The disruptive scenario category includes adverse conditions that are extremely unlikely (e.g., volcanism) but that could, if they were to happen, significantly reduce the capability of the repository to isolate waste. In addition to analyses of scenarios in these two categories, the TSPA analyzes a separate scenario for human intrusion, which assumes a drill hole penetrating the repository during a hypothetical groundwater exploration operation.

The following are examples of specific disruptive conditions that were considered in the TSPA evaluation:

- **Igneous activity**—Magmatic processes causing releases of radioactive wastes directly (i.e., to the atmosphere) and/or indirectly (i.e., in the subsurface) into the environment (disruptive scenario)

- **Seismic activity**—Vibratory ground motion and fault displacement potentially causing damage to the engineered barriers and/or alteration of the performance attributes of the natural barriers (nominal scenario)

- **Human intrusion**—Inadvertent drilling through the repository and penetrating a single waste package, causing radionuclide releases to the groundwater aquifer (human intrusion scenario).

Igneous activity (or, alternatively, volcanism) was the principal disruptive scenario retained after the comprehensive screening/selection process described in Section 4.3.1. Potential seismic effects on the underground facilities and waste packages were screened out (i.e., excluded from consideration) because the waste packages would not be adversely damaged by design basis rockfalls or vibratory ground motion (CRWMS M&O 2000ex, Section 6.2). However, because vibratory ground motion from seismic events might damage the commercial spent nuclear fuel cladding, the effect of this potential damage to cladding by a discrete seismic event is included in the TSPA model in the nominal scenario. The frequency assumed for this event is 1.1×10^{-6} per year. For this analysis, when the vibratory ground motion event occurs, all commercial spent nuclear fuel cladding in the repository is assumed to fail by perforation, and further cladding degradation is calculated according to the cladding degradation. A drilling scenario of inadvertent human intrusion is considered in a separate TSPA calculation.

The following sections provide background information relevant to the disruptive scenarios that have been considered in the TSPA.

4.3.2.1 Volcanic/Igneous Activity

For more than two decades, scientists have performed extensive volcanism studies at Yucca Mountain. Their studies identified the location, age, volume, geochemistry, and geologic setting of past volcanic activity in the area. The results from these studies are described in *Yucca Mountain Site Description* (CRWMS M&O 2000b, Section 12.2). Although scientists cannot predict future volcanic activity with total certainty, the resulting data provide a comprehensive basis for estimating the probability of future volcanic activity and for determining the effects on people and the environment if volcanic activity were to disrupt the potential repository (CRWMS M&O 2000f, Section 3.1).

4.3.2.1.1 Past Volcanic Activity in the Yucca Mountain Region

Volcanoes have played an important role in the development of the Yucca Mountain region. From 15 million to about 7.5 million years ago, a series of large, silicic, explosive volcanic eruptions occurred in the region. These eruptions produced dense clouds of incandescent volcanic glass (silica), ash, and rock fragments, which melted or compressed together to create layers of rock called tuff. Some of the explosive volcanoes in the Yucca Mountain region formed large calderas as much as 20 km (12 mi) in diameter. Calderas are circular depressions that form when large volumes of magma erupt rapidly, causing the volcano's surface to collapse.

The large-volume, silicic type of volcanic activity no longer occurs in the Yucca Mountain region and has not occurred for more than 7.5 million years. The layers of ash-fall and ash-flow tuff formed by these eruptions have since been disrupted by faulting and erosion. The subsurface bedrock units of Yucca Mountain are made up of ash-fall and ash-flow tuffs that were deposited approximately 13 million years ago, during the episode of silicic volcanism.

Basaltic volcanism began during the latter part of the caldera-forming phase, as rates of extension of the earth's crust waned; small-volume basaltic volcanism continued in the Quaternary Period (the past approximately 2 million years). Collectively, the calderas and basaltic eruptions in the Yucca Mountain region are called the southwestern Nevada volcanic field (Sawyer et al. 1994). Approximately 99.9 percent of the volume of the southwestern Nevada volcanic field erupted between 15 and 7.5 million years ago. The last 0.1 percent of eruptive volume of the volcanic field, consisting entirely of basalt, erupted since 7.5 million years ago. Considered in terms of total eruption volume, frequency of eruptions, and duration of volcanism, basaltic volcanic activity in the Yucca Mountain region defines one of the least active basaltic volcanic fields in the western United States (CRWMS M&O 2000ez, Section 6.2).

In the Yucca Mountain region, there are more than 30 basaltic volcanoes that were formed between 9 million and 80,000 years ago. These volcanoes can be separated into two distinct periods of volcanism that are separated both temporally and spatially. The older basaltic volcanoes formed between about 9 and 7.3 million years ago (during the Miocene epoch). The younger (post-Miocene) basaltic volcanoes erupted between approximately 5 million and 80,000 years ago. As shown in Figure 4-158, the general location of the younger, post-Miocene volcanoes shifted substantially to the southwest (CRWMS M&O 2000ez, Section 6.2).

The post-Miocene volcanoes were formed during at least six different episodes that occurred within 50 km (31 mi) of the proposed Yucca Mountain repository (Figure 4-158). Three of these episodes produced six cinder cones that are in or near the Crater Flat basin, within 20 km (12 mi) of Yucca Mountain (Figure 4-159). The latest volcanic episode, about 80,000 years ago, created the Lathrop Wells Cone, about 18 km (11 mi) south of the potential repository site.

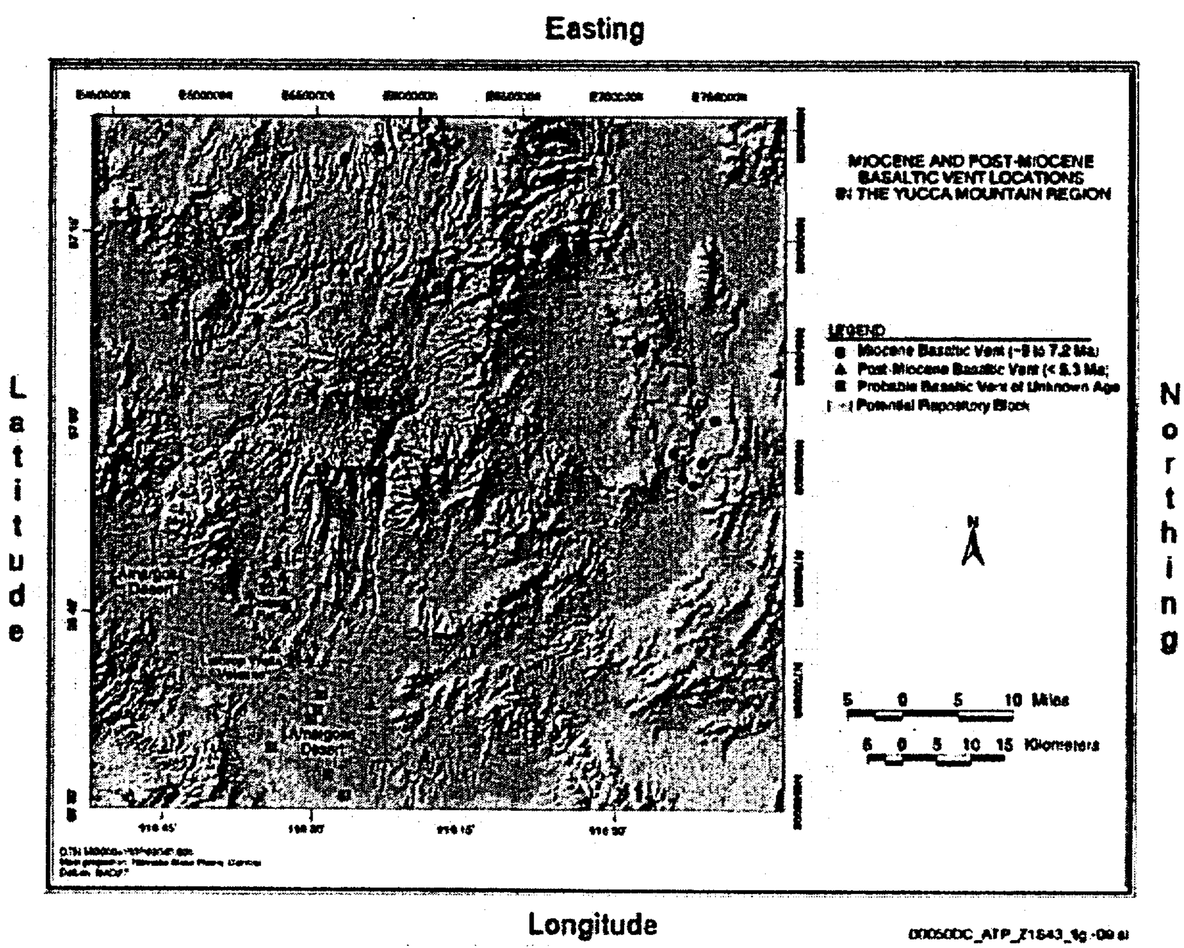

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Figure 4-158. Location of Miocene (Circles) and Post-Miocene (Triangles) Basaltic Vents of the Yucca Mountain Region

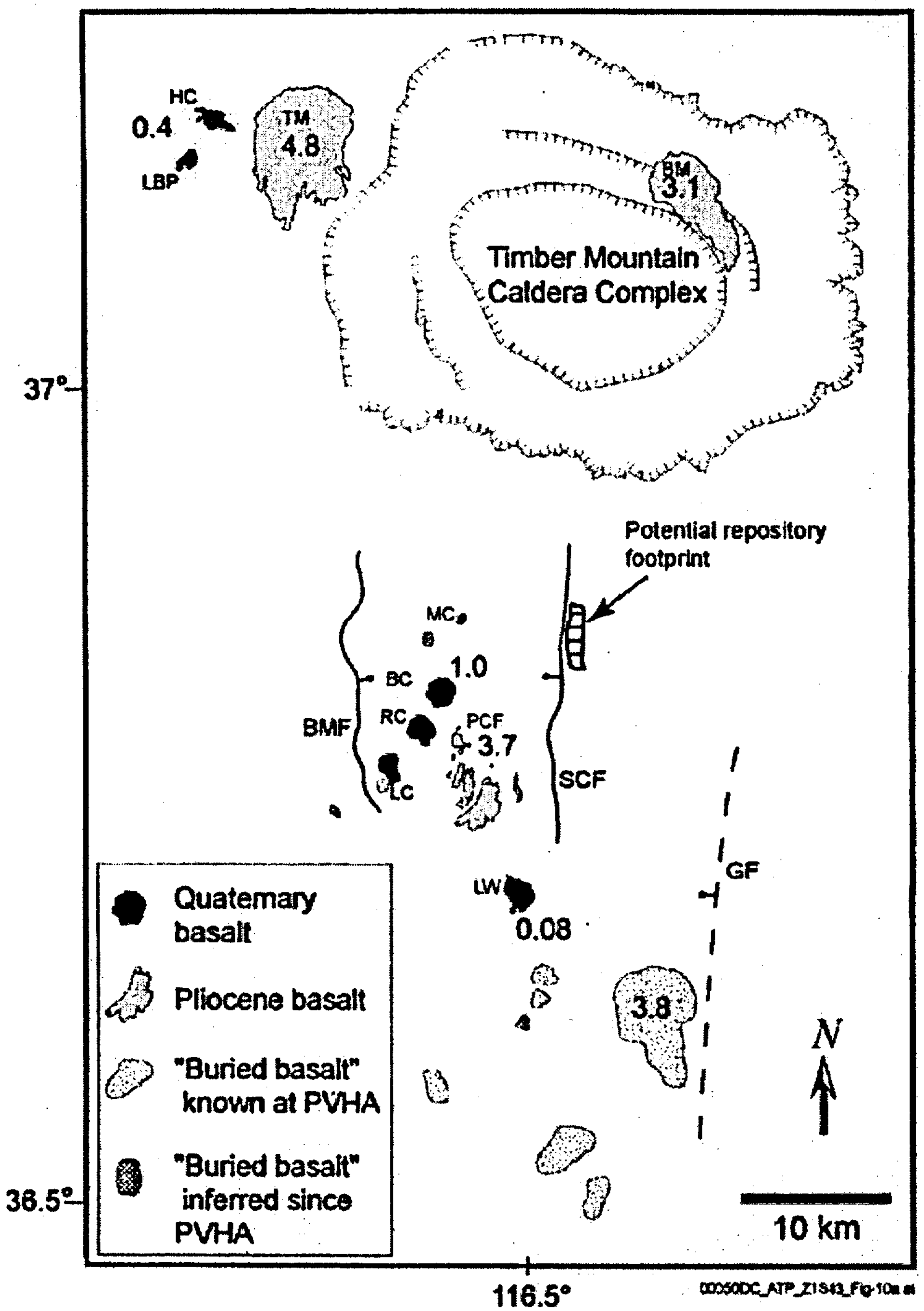

Figure 4-159. Location and Age of Quaternary (<2 Million Years) and Pliocene (2 to 5 Million Years) Volcanoes (or Clusters where Multiple Volcanoes have Indistinguishable Ages) and Probable Buried Basalt in the Yucca Mountain Region

Numbers by each volcano indicate approximate age in millions of years. BM = Buckboard Mesa; TM = Thirsty Mesa; HC = Hidden Cone; LBP = Little Black Peak; MC = Makani Cone; BC = Black Cone; RC = Red Cone; LC = Little Cones; PCF = Pliocene Crater Flat; LW = Lathrop Wells; BMF = Bare Mountain fault; SCF = Solitario Canyon fault; GF = Gravity fault. PVHA = *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada* (CRWMS M&O 1996b). Buried basalt is assumed to be post-Miocene based on the age of one buried basalt sampled by drilling. Source: CRWMS M&O 2000ez, Figure 3.

Basaltic volcanoes form from magma that has a low silica and water content. In the southern Great Basin, basaltic volcanoes generally do not erupt as violently as magmas with higher silica and water content. Basaltic volcanoes in the Yucca Mountain region typically form cinder cones associated with small-volume lava flows. However, if the water content is high enough or the magma encounters groundwater during its ascent, explosive phases can also occur, resulting in eruption of an ash plume and deposition of an ash blanket. The youngest basaltic volcanoes in the Yucca Mountain region contain deposits that record moderately violent eruptions that may have produced ash plumes 5 to 10 km (3 to 6 mi) high, along with evidence for less violent and even nonexplosive eruptions.

Most observed basaltic eruptions begin as fissure eruptions, discharging magma where a dike (a vertical, tabular sheet of intrusive magma) intersects the earth's surface. They rapidly become focused at one or more vents into semicircular conduit eruptions. Volcanoes in the Yucca Mountain region are each fed by one main dike, along which a central cone and other vents may form, although subsidiary dikes are also present (CRWMS M&O 2000fa, Section 6.1). Typical basaltic dikes in the Yucca Mountain region are approximately 1.5 m (5 ft) wide (CRWMS M&O 2000fa, Section 6.1) and about 1,000 to 5,000 m (3,000 to 16,000 ft) long (CRWMS M&O 2000ez, Figure 13).

4.3.2.1.2 Probabilistic Volcanic Hazard Analysis

To assess the probability of volcanic activity disrupting a repository, the DOE has performed numerous analyses and conducted extensive volcanic hazard assessments. A panel of ten experts representing a wide range of expertise in the fields of physical volcanology, volcanic hazards, geophysics, and geochemistry were assembled to evaluate the volcanic hazard. The scientists reviewed extensive information presented by representatives of the DOE, U.S. Geological Survey (USGS), State of Nevada, NRC, and others regarding the timing and location of possible future volcanic activity near Yucca Mountain. This study included a careful evaluation of the uncertainties in all the analyses. The expert panel devoted considerable effort to evaluating the existing data, testing alternative models and hypotheses, and ultimately, incorporating a wide variety of alternative models and parameters in their evaluations. Their evaluations (elicitations) were then combined to produce an integrated assessment of the volcanic hazard that reflects a range of alternative interpretations.

To estimate the probability of future volcanic activity at Yucca Mountain, the panel of experts used sophisticated modeling techniques documented in *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada* (CRWMS M&O 1996b). As defined in *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada*, a volcanic event is the formation of a volcano (with one or more vents) from the ascent of basaltic magma through the crust as a dike or system of dikes (CRWMS M&O 1996b, Appendix E). For the hazard analysis, the panel of experts considered a volcanic event as a point in space representing a volcano and an associated dike having length, azimuth, and location relative to the point event (CRWMS M&O 2000ez, Figures 10 and 12). This hazard analysis evaluated the annual probability of a future basaltic dike intersecting the subsurface area of the potential repository, based on considerations of the locations and recurrence rates of past volcanic activity in the region.

The hazard analysis models are based on data from Yucca Mountain volcanic studies, along with other data and observations from analogue studies of both modern and ancient volcanic eruptions. From these studies, scientists infer how and where magmas form and the processes that control the timing and location of magma ascent through the earth's crust. The panel of experts agreed that future volcanism is more likely to occur within or near existing clusters of geologically recent volcanism than elsewhere in the Yucca Mountain region. While the experts considered the entire 15-million-year history of volcanism in the Yucca Mountain region, they assigned the highest weights for assessing the volcanic hazard in the probabilistic analysis to the past 5 million years. They also emphasized the Crater Flat basin because of the frequency of past volcanic activity there and its proximity to the potential repository (Figure 4-159). One difficulty, however, in evaluating past basaltic volcanic activity in the area is that evidence of basaltic volcanoes, particularly those that are older than 2 million years, may have been eroded or buried by younger sediments. The panel of experts recognized the possibility that there may be additional undetected basaltic volcanoes in the Yucca Mountain region and factored this into their uncertainty estimates for the number of volcanic events that have occurred.

The results of the probabilistic volcanic hazard analysis (CRWMS M&O 1996b) form the basis for probabilistic volcanic risk estimates that account for the repository layout described in this report and the probability of eruption through the repository, conditional on dike intrusion within the repository footprint. These latter results are included in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a).

The results of the hazard analysis estimate that 1.6×10^{-8} igneous events per year could be expected to disrupt the potential repository (CRWMS M&O 2000ez, Section 6.5.3). This translates to approximately one chance in 6,250 of an igneous event disrupting the repository during the first 10,000 years after repository closure. This is the probability of a future basaltic dike intersecting the subsurface area of the potential repository (intrusive scenario). If a dike does intersect the repository, analysts estimate about a 77 percent chance that a volcano would form at the surface with magma flowing through the repository (eruptive scenario) (CRWMS M&O 2000ez, Table 13a). This translates to approximately 1 chance in 7,700 of a volcano forming above the repository during the first 10,000 years. The annualized probabilities for both disruptive events are just slightly greater than the probability cutoff of 10^{-8}/yr; therefore, both intrusive and eruptive igneous scenarios have been included in the TSPA. Earlier versions of the TSPA analyses used lower estimates of the likelihood that magma contacting the repository would erupt at the surface (a probability of 0.36). Nevertheless, both intrusive and eruptive scenarios were also included in those analyses.

Analysis of new data collected in the Yucca Mountain region since the completion of the hazard assessment demonstrates the thoroughness of the results. Post-elicitation studies by the NRC (Connor et al. 1997) provided evidence to support the possibility of a greater volume for one of the volcanic centers in the Crater Flat basin and an additional volcanic center in the Amargosa Valley. Sensitivity studies showed that these new data did not significantly affect the results of DOE's hazard assessment (Brocoum 1997). The DOE will continue to monitor data and will incorporate significant new information into future technical and licensing documents.

4.3.2.1.3 Consequence Analyses for Volcanic/Igneous Disruptive Events

The DOE evaluated the possible consequences of volcanic activity disrupting the potential repository and estimated the risk to people and the environment that would result from such a disruption. Models of the consequences of an igneous intrusion into, or a volcanic eruption through, a repository at Yucca Mountain require specific information about the nature of the igneous event and the response of the repository to intrusion. This analysis considered the full range of basaltic eruptive processes that have occurred in the Yucca Mountain area during the Quaternary Period, from explosive to nonviolent basaltic eruptions. Information used in the TSPA-SR model to characterize these intrusive and eruptive processes comes from three sources: (1) examination of the geologic record of past intrusive and eruptive events in the Yucca Mountain region, (2) observations of eruptive processes during analogous modern volcanic events elsewhere in the world, and (3) consideration of the range of physical processes that might occur during the interaction between the repository and an igneous dike. The first two sources of information are described in the analysis model reports *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* (CRWMS M&O 2000ez) and *Characterize Eruptive Processes at Yucca Mountain, Nevada* (CRWMS M&O 2000fa). The analysis model report *Dike Propagation Near Drifts* (CRWMS M&O 2000fb) and the calculation *Waste Package Behavior in Magma* (CRWMS

M&O 1999p) provide additional information regarding dike and repository interactions.

Figure 4-160 is a schematic illustration of the hypothetical igneous activity modeled in the analysis. Two possible scenarios for igneous disruption are included in the consequence analysis: a model for volcanic eruptions that intersect drifts and bring waste to the surface; and a model for igneous intrusions that damage waste packages and expose radionuclides to groundwater transport processes. These models are described in detail in *Igneous Consequence Modeling for the TSPA-SR* (CRWMS M&O 2000fc) and represented schematically in Figure 4-161.

The scenario for a volcanic eruption assumes that magma erupts through a section of the repository, forming a volcano at the surface (Figure 4-161a). This scenario assumes that an igneous dike rises through the earth's crust and intersects one or more drifts in the repository. An eruptive conduit (the vertical cylindrical passageway through which magma and pyroclasts move upward) forms somewhere along the dike as it nears the land surface, feeding a volcano at the surface. Waste packages in the path of the conduit are destroyed, and the waste is available to be entrained in the eruption. Volcanic ash is contaminated, erupted, and then transported by wind. Ash settles out of the plume as it is transported downwind, resulting in an ash layer on the land surface. The receptor receives a radiation dose from various pathways associated with the contaminated ash layer.

The scenario begins with an eruptive event, which is characterized in the TSPA by both its probability (CRWMS M&O 2000ez, Section 6.5.3) and its physical properties, such as energy and volume of the eruption, composition of the magma, and properties of the pyroclastic ash. Interactions of the eruption with the repository are described in terms of the damage to the engineered barrier system and the waste package. Characteristics of the waste form in the eruptive environment are described in terms of waste particle size. Atmospheric transport

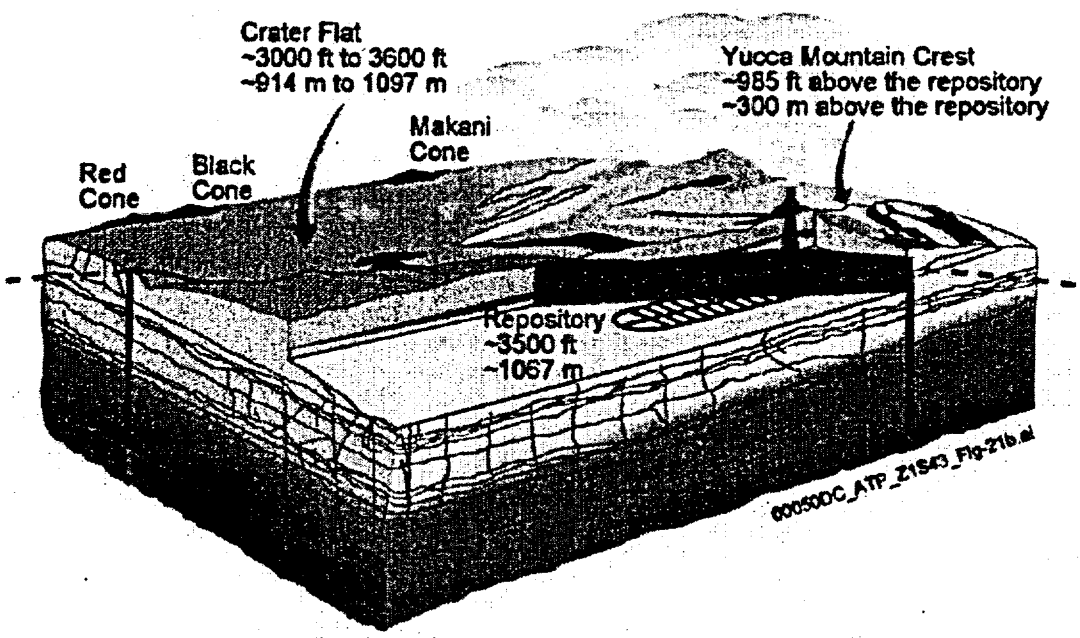

Figure 4-160. Schematic Illustration of Hypothetical Igneous Activity at Yucca Mountain
In the hypothetical case shown here, an intrusive dike rises through the earth's crust and intersects the repository. An eruptive conduit forms above the dike and feeds a volcano at the earth's surface. TSPA scenarios include cases both with and without eruptions that intersect the repository. Elevations of Crater Flat and the potential repository horizon are distances above sea level.

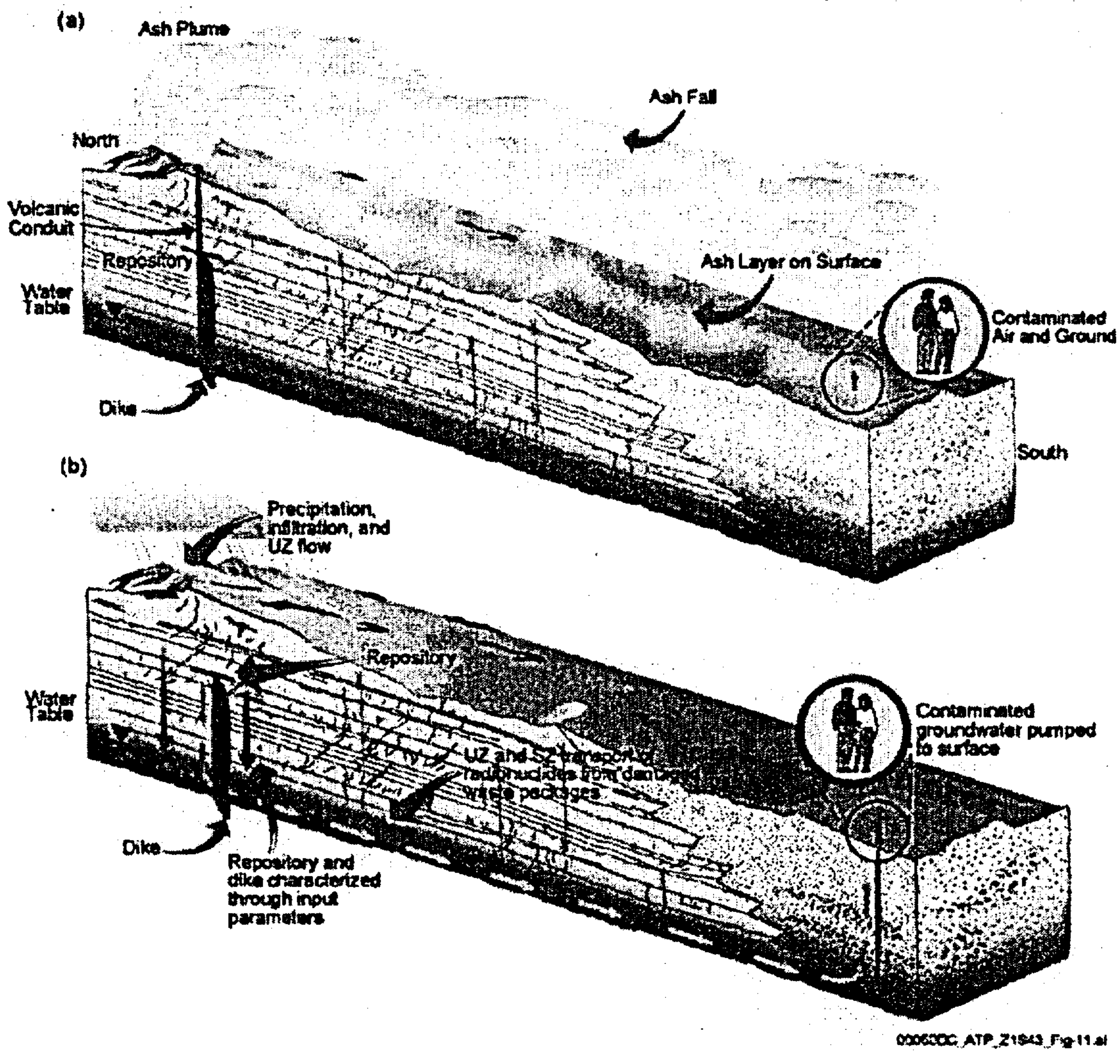

Figure 4-161. Schematic Representation of the Two Volcanism Scenarios Analyzed for TSPA-SR
(a) Volcanic eruption at Yucca Mountain, showing development of an eruptive conduit through a part of the repository, entrainment of waste particles in an ash cloud, and deposition of contaminated ash downwind of the potential repository. (b) Igneous intrusion at Yucca Mountain, showing the intersection of one or more emplacement drifts by an ascending dike followed by flow of magma in drifts, engulfing and damaging waste packages, and subsequent transport of radionuclides by groundwater moving through the solidified intrusion. UZ = unsaturated zone; SZ = saturated zone.

of waste in the volcanic ash plume begins with entrainment of waste particles in the pyroclastic eruption and is affected by wind speed and direction. Biosphere dose conversion factors are developed specifically for exposure pathways relevant to atmospheric deposition of contaminated ash, rather than the groundwater pathways considered for nominal performance. As a final step, the volcanic eruption biosphere dose conversion factors are used to determine radiation doses resulting from exposure to contaminated volcanic ash in the accessible environment, approximately 18 km (11 mi) from the repository.

The other scenario in the analysis models the possible effects of a basaltic dike that intersects a section of the repository and partially or completely engulfs waste packages in magma (Figure 4-161b). This may or may not be accompanied by an eruption from the surface of the mountain. Radionuclide releases from waste packages damaged by the intrusion are then available for transport in groundwater. The rate of transport depends on the solubility limits of the waste and the availability of water. The movements of radionuclides released by this type of an event are modeled directly in the TSPA using existing flow-and-transport models.

This scenario begins with an intrusive event (dike intersection), which is characterized in the TSPA by its probability and physical properties. Although the intrusion damages waste packages and other components of the engineered barrier system, it does not significantly alter the long-term flow of water through the mountain. Possible effects of a dike intrusion on the mountain hydrology in the unsaturated and saturated zones are discussed in *Features, Events, and Processes: Disruptive Events* (CRWMS M&O 2000ex, Section 6.2.8). Based on natural analogue sites, there is no indication of extensive hydrothermal circulation and alteration related to magmatic intrusion. In particular, natural analogue studies at sites on the Nevada Test Site show that alteration is limited to less than 10 m (30 ft) into the country rock adjacent to a dike intrusion (CRWMS M&O 2000ex, Section 6.2.9). Therefore, the disruptive event scenario uses nominal models to describe groundwater flow and radionuclide transport through the mountain.

For calculation of the annual dose resulting from radionuclides that are transported in groundwater following a disruptive igneous event, conditions in the biosphere at the location of the receptor are assumed to be the same as the conditions for nominal performance. Biosphere dose conversion factors for this pathway are therefore the same as those used in the nominal scenario. Because the total expected annual dose in the TSPA models is the sum of probability-weighted doses from both the nominal and disruptive scenarios, any additional increment of dose due to nominal processes that might occur following an igneous disruption is appropriately included in the overall analysis.

The TSPA-SR conceptual models take a conservative approach to modeling uncertainty in several respects. For the purposes of the analysis, the contents of all packages that are fully or partially damaged by an eruption (i.e., that lie in part or entirely within the circumference of the conduit, as described in Section 4.4.1) are assumed to be fully available for entrainment in the eruption. Likewise, it is conservatively assumed that any waste package that is partially or completely intersected by an intrusive dike is fully destroyed. The model does not take credit for the possibility of the magma encapsulating the waste and waste package, which could slow or even prevent water from reaching the waste. In the eruptive scenario, the entire volume of erupted material is conservatively assumed to have been involved in a violent phase of eruption. Observations of both modern and past analogue volcanoes indicate that the violent phases account for only a portion of the total eruption. This assumption overestimates, perhaps significantly, the amount of energy in the eruption and, therefore, the amount of ash transported away from the site. The TSPA evaluates the risk to people and the environment from both disruptive igneous event scenarios. These include (1) doses from the direct release of contaminated ash from an explosive volcanic eruption and (2) doses resulting from the release of radionuclides into the groundwater from waste packages damaged by magma intrusion. The results of these analyses are discussed in Section 4.4.3. Indirect effects that result from volcanic activity outside the repository (e.g., changes to the hydrologic and mineralogical properties of the rock or alteration of water flow and transport) have such low consequences that they are not evaluated further (CRWMS M&O 2000ex).

4.3.2.2 Seismic Activity

The geologic setting of a region influences potential earthquake effects by controlling:

- Location and size of earthquakes
- Potential for the ground's surface to rupture by faulting
- Amount of ground shaking at a specific site from earthquakes at various distances.

During site characterization, the DOE performed extensive studies at Yucca Mountain to estimate the potential sizes and frequencies of future earthquakes and to determine the level of ground motion and fault displacement that might affect potential repository facilities, both on the surface and underground. The DOE has used the results from these studies to design repository facilities that will withstand future earthquakes and to assess the long-term performance of the total repository system.

Scientists cannot predict the exact location and timing of future earthquakes. However, through intensive study of an area's surface and underground geology, with particular attention to past faulting, scientists can estimate the frequency and size of future earthquakes, the potential intensity of ground movement, and the possible effects from earthquakes on the area's geologic features and man-made structures.

The Yucca Mountain region is one of the most intensively studied areas in the world. Since 1978, scientists have collected and analyzed data on the geologic features of the surface and underground environments. These features provide information on the area's past seismic activity, which is important in estimating the characteristics of future earthquakes. Using these studies, scientists rate the Yucca Mountain region as having low to moderate seismicity (Figure 4-162) (CRWMS M&O 2000fd, Section 6.3.1).

Most of the movement in the earth's crust that formed the mountains and valleys of the southern Nevada landscape ended about 10 million years ago, but slow movement has continued into the present. Some of this movement occurs along faults, which are zones of weakness in the earth's crust. Future movement on some faults will produce future earthquakes. Therefore, intensive study has focused on the faults in the Yucca Mountain region to determine which faults are likely to move in the future and to estimate the potential magnitude and frequency of those earthquakes.

Scientists have used the data from site characterization studies to assess the seismic hazard at the site by defining the potential for ground shaking and fault rupture related to earthquakes. The type of analysis used is called a probabilistic seismic hazard analysis. This type of analysis provides estimates on where and how often earthquakes might occur and on how much fault displacement and ground motion could result. To assess the seismic hazard for Yucca Mountain, scientists factored in different interpretations to account for uncertainties in evaluation of the data for each geologic feature.

Recent earthquakes near Yucca Mountain have been consistent with the seismic hazard analysis for the Yucca Mountain site. For example, in 1999 a magnitude 4.7 M_w (moment magnitude) earthquake occurred at Frenchman Flat about 45 km (28 mi) east of Yucca Mountain (for an earthquake of this size, moment magnitude is approximately equal to magnitude on the Richter scale). This was a moderate-magnitude event in a zone that scientists had identified as a seismic source. This earthquake did not exceed the ground motion estimates from the seismic hazard analysis. (See Sections 6.3 and 6.5 in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* [CRWMS M&O 2000fd] for a discussion of seismic source characterization.) The results from the seismic hazard analysis are a sound basis for designing repository facilities to withstand potential earthquakes and for assessing future repository performance.

Engineers use proven techniques to design structures to withstand the potential earthquakes within that area. The repository surface facilities, where waste would be received, prepared for emplacement, then moved into the repository, would be subject to stronger earthquake ground shaking than subsurface facilities. (See Section 4.3.2.2.1 for more on the effects of seismic activity underground.) Extensive experience in designing and operating critical facilities, such as nuclear power plants, will be relied on in the design of the structures used during repository operations, so they will perform their safety functions during and after an earthquake. After all the waste is emplaced underground, the risks related to seismic activity would decrease. However, a strong earthquake could cause rock falls in the emplacement drifts or alter the pathways followed by groundwater. Scientists have studied these potential conse-

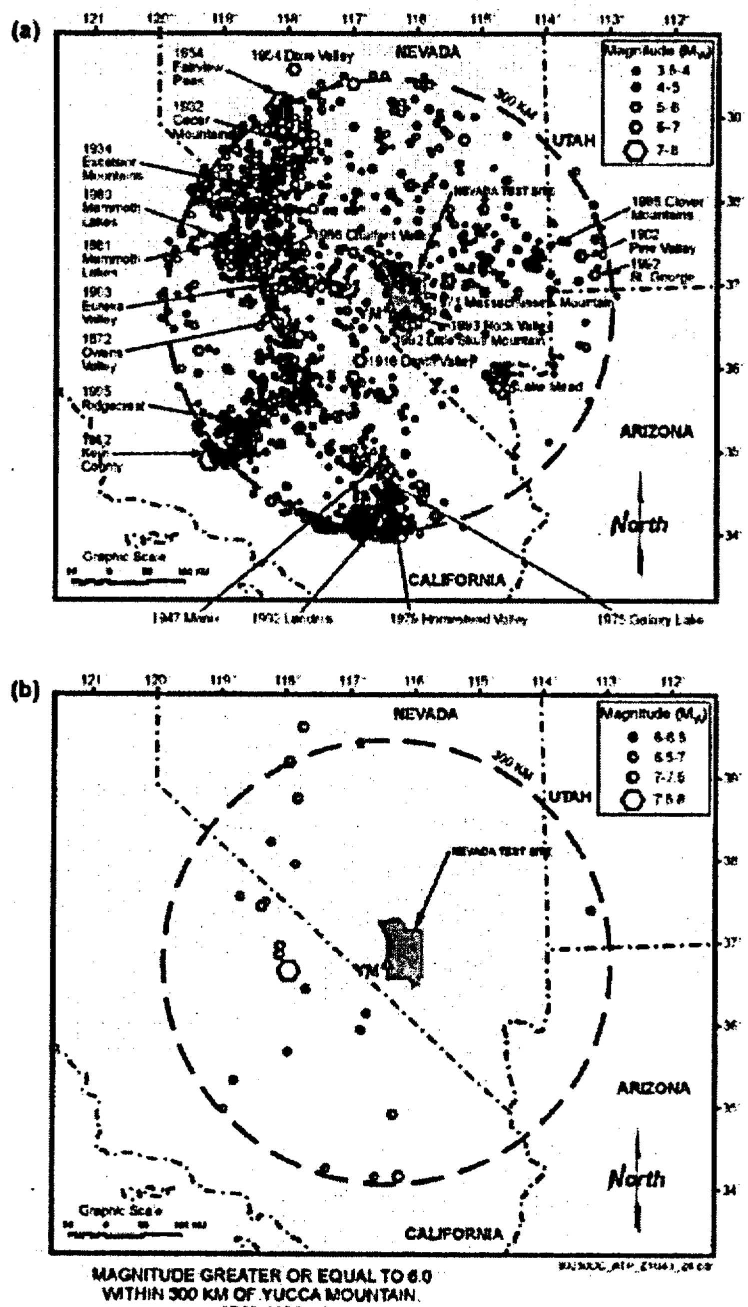

Figure 4-162. Historical Seismicity (1868 to 1996) Showing Events of M_w 3.5 or Modified Mercalli Intensity III and Larger within 300 km (186 mi) of Yucca Mountain

This seismicity catalog was compiled from a variety of sources. Coverage of older seismicity is sparse because of the absence or limited availability of seismographic coverage in the late 1800s and early 1900s. The cluster of earthquakes near the southern border of the Nevada Test Site represents the 1992 Little Skull Mountain earthquake and its numerous aftershocks; many of the events in the northern half occurred in response to underground nuclear weapons tests. Part b shows events of M_w 6 and larger within this time period. Earthquakes designated by name and year of occurrence are discussed in Section 12.3 of the *Yucca Mountain Site Description* (CRWMS M&O 2000b). For a more detailed discussion of these issues and how an earthquake catalog is used to assess seismic hazard, see Section 12.3.3 of the *Yucca Mountain Site Description* (CRWMS M&O 2000b) and Appendix G of *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada* (Wong and Stepp 1998).

quences and concluded that it is extremely unlikely that the consequences would be significant to repository performance. (See Section 4.3.2.2.3 for a discussion of fault displacement effects.)

4.3.2.2.1 Effects of Seismic Activity Underground

Underground openings are less likely to sustain damage from earthquakes than structures on the surface. This is because ground shaking is stronger on the surface than underground. When an earthquake occurs deep underground, locations at the surface receive ground motion energy simultaneously from the upward-traveling waves and from waves reflected back at the earth's surface. In addition, subsurface rock generally is stronger than weathered near-surface rock, which results in a smaller ground motion at depth.

A seismometer (an instrument that records earthquake waves) at the ground level and another in the Exploratory Studies Facility recently measured seismic waves from a 3.5 M_w earthquake at Frenchman Flat (this event was an aftershock of the 4.7 M_w earthquake described previously). Recordings from this earthquake, as shown in Figure 4-163, clearly indicate the decrease in amplitude of ground motion deep within the mountain (Savino et al. 1999). Scientists have observed this effect around the world for underground structures. For example, tunnels near the 1995 Kobe,

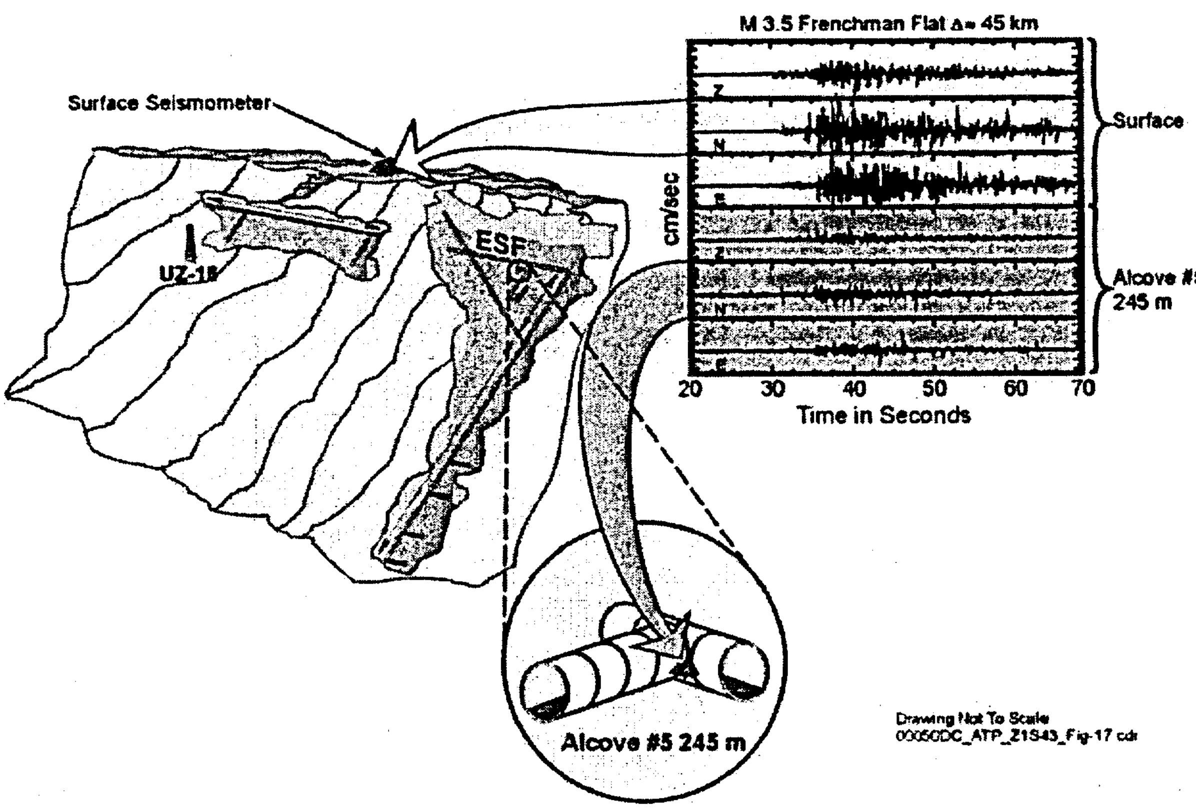

Figure 4-163. Recordings of Frenchman Flat Earthquake at the Ground Surface and the Thermal Test Alcove 245 m (804 ft) Underground

The seismograms for the surface and underground at the Thermal Test Alcove of the Exploratory Studies Facility (i.e., Alcove #5, at 245 m depth) are to the same vertical scale. M = magnitude; Δ = distance; Z = up–down; N = north–south; E = east–west; ESF = Exploratory Studies Facility. Source: Savino et al. 1999.

Japan earthquake (6.9 M_w) experienced no major damage despite high surface ground motion and extensive damage to surface facilities (Savino et al. 1999).

4.3.2.2.2 Probabilistic Seismic Hazard Analysis

The probabilistic seismic hazard analysis identifies the potential earthquake ground motion and fault displacement that could occur at the Yucca Mountain site. The results from this analysis were incorporated into estimates of seismic consequences and used in designing the repository's facilities. The following paragraphs describe the DOE's methods for performing the seismic hazard analysis (CRWMS M&O 2000fd).

The probabilistic seismic hazard analysis involved a multistep process. First, scientists identified the location of potential earthquake sources and defined their characteristics. Next, they estimated how frequently earthquakes of various magnitudes might occur at each source location. In the third step, experts calculated potential earthquake effects at Yucca Mountain, including the level of vibratory ground motion and amount of fault displacement, given earthquakes of a particular magnitude. Finally, they combined all of the information from the previous steps into "hazard curves" that show the probability of exceeding different levels of ground motion or fault displacement at a particular location during a specific period in time.

The method for performing the seismic hazard analysis of Yucca Mountain is state-of-the-practice and consistent with recent guidance developed by government agencies (e.g., the U.S. Army Corps of Engineers, the USGS). The NRC uses this method to evaluate the safety of existing nuclear power plants, and it would be the basis for licensing new plants (CRWMS M&O 2000fd, Section 6.1.4; CRWMS M&O 2000f). Specific information provided by the probabilistic seismic hazard analysis includes:

- The location of seismic sources that could contribute to fault displacement and vibratory ground motion at Yucca Mountain
- Estimates of the maximum magnitude of potential earthquakes from each seismic source (i.e., the largest earthquake the source can generate)
- Estimates of the frequency or recurrence rate of earthquakes having various magnitudes, up to the probable maximum magnitude
- Characterization of ground motion attenuation (decrease in amplitude of ground motion with distance from the source)
- Estimated probabilities for both fault displacement and vibratory ground motion
- Incorporated uncertainties into the analyses to reflect the range of views of experts.

Many scientists and engineers contributed to these activities. These individuals were associated with universities (including the University of Nevada, Reno and the University of Utah), government agencies (including the DOE, USGS, and U.S. Bureau of Reclamation), and private companies.

Seismic Source Location and Geometry—A seismic source is a region of the earth's crust that has certain characteristics indicating that earthquakes could originate there. In the probabilistic seismic hazard analysis, seismic sources can be of two basic types: fault sources and areal sources.

Fault sources are known fractures in the earth's crust containing characteristics that indicate past movement along the fault's surfaces. A fault is considered to have the potential to move in the future if it has moved in the past 2 million years (the Quaternary Period). Evidence from historically active faults around the world indicates that, in general, faults that show characteristics of having moved in the recent past, or "active faults," are those most likely to sustain future movement. Studies of faults in the Yucca Mountain region have focused on active and potentially active faults.

To represent the full range of possible fault rupture patterns and interactions near Yucca Mountain, experts used various combinations of possible fault orientations and behaviors in their analyses of each potentially active fault. They also used alternate lengths for each fault to compensate for uncertainties in geologic mapping and different rupture patterns. Figure 4-164 shows the faults that were considered in the seismic analysis. Table 4-32 shows selected fault parameters for potentially significant faults within 10 km (6.2 mi.) of the repository that potentially could rupture independently (that is, rupture of a single fault and not simultaneous rupture of multiple faults). The slip rates are relatively low in comparison with rates for significant regional faults (such as the Furnace Creek and Death Valley faults, which have slip rates of 2.5 to 8 mm/yr [0.1 to 0.3 in./yr]).

Areal sources represent areas where experts believe that potential earthquakes could occur on faults not singularly recognized as significant earthquake sources, such as buried faults. These areas are treated as having relatively uniform earthquake frequency and maximum earthquake magnitudes.

Maximum Earthquake Magnitudes—Experts used two basic approaches to estimate the

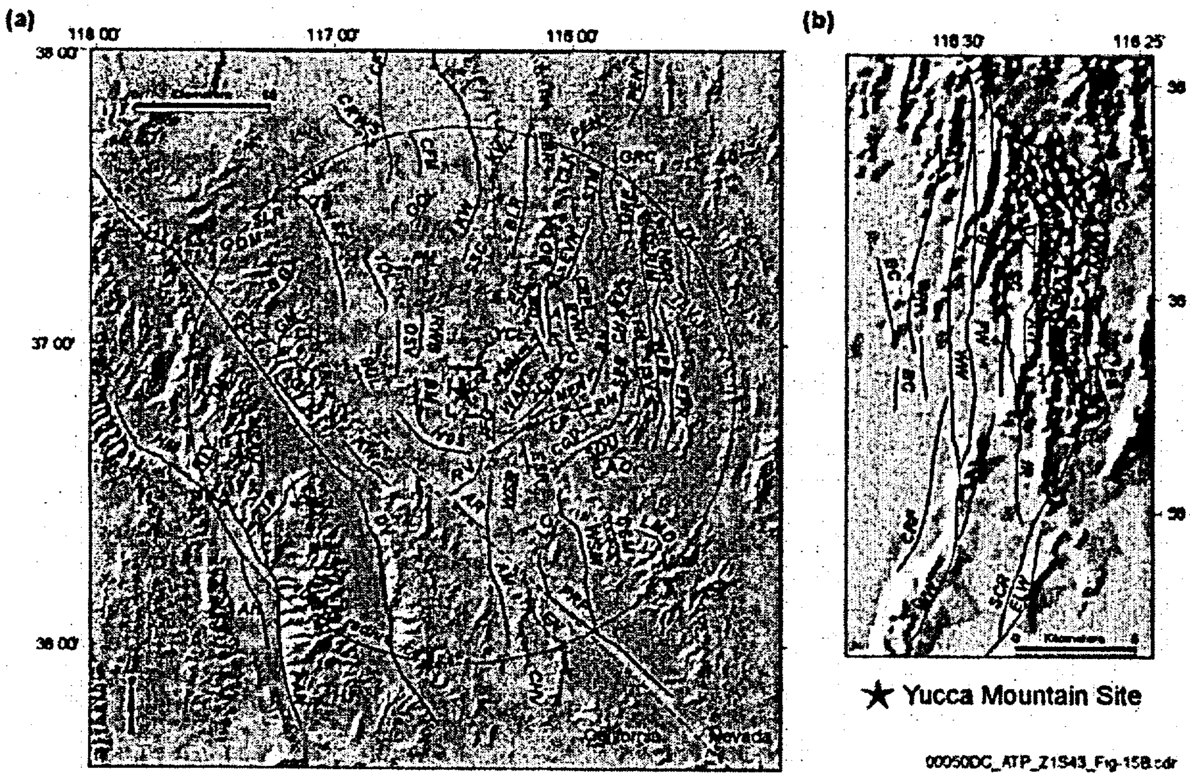

Figure 4-164. Known or Suspected Quaternary Faults and Potentially Significant Local Faults within 100 km of Yucca Mountain

(a) Known or suspected Quaternary faults within 100 km (62 mi) of Yucca Mountain; the two faults of interest are the Furnace Creek (FC) and Death Valley (DV) faults.

(b) Detail of (a), showing known or suspected faults near Yucca Mountain; these faults are the Abandoned Wash (AW), Black Cone (BC), Boomerang Point (BP), Crater Flat (CRF), Drill Hole Wash (DHW), Dune Wash (DW), East Busted Butte (EB), East Lathrop Wells (ELW) Fatigue Wash (FW), Ghost Dance (GD), Iron Ridge (IR), Midway Valley (MDV), Paintbrush Canyon (PC), Solitario Canyon (SC), Stagecoach Road (SCR), Sundance (SD), and Windy Wash (WW) faults.

Also see Figure 1-14 for the locations of the block-bounding and intrablock faults relative to the Exploratory Studies Facility and the potential repository block. For detailed identification of each fault labeled with initials in (a) but not identified in these notes, see the *Yucca Mountain Site Description* (CRWMS M&O 2000b, Figure 12.3-12). Source: CRWMS M&O 2000f, Figures 2-8 and 2-9.

Table 4-32. Potentially Significant Faults and Fault Parameters within 10 km (6.2 mi) of the Potential Repository

Fault Name	Rupture Length[a] (km)	Distance[b] (km)	Slip Rate[a] (mm/yr)
Solitario Canyon	16 to 18.7	1	0.01 to 0.03
Iron Ridge	6.5 to 8.5	2.5	0.002 to 0.004
Bow Ridge	6.7 to 8	2.5	0.002 to 0.003
Fatigue Wash	9.5 to 17	3.5	0.002 to 0.009
Paintbrush Canyon	12 to 19.4	4	0.002 to 0.017
Windy Wash	5 to 27	4.5	0.003 to 0.03
North Crater Flat	6.5 to 13.3	6	0.001 to 0.003
South Crater Flat	6.1 to 8.1	8	0.001 to 0.008
Stagecoach Road	4.5 to 10	10	0.016 to 0.05

NOTES: [a]Range of preferred values interpreted by the experts.
[b]Approximate shortest distance to repository.
Only significant and potentially independent fault sources are included here; see Appendix E of *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada* (Wong and Stepp 1998) for a complete discussion of all local fault sources, including multiple fault rupture scenarios. Source: Modified from CRWMS M&O 2000fd, Table 6.

maximum magnitudes of potential earthquakes in the Yucca Mountain region. The primary approach was based on estimates of the maximum dimensions of fault rupture. Multiple sources of uncertainties were considered in estimating physical dimensions of maximum rupture on faults (e.g., uncertainties in rupture length, rupture area, and displacement per event). Experts then compared these estimated dimensions with the estimated dimensions of ruptured faults and known magnitudes of earthquakes observed throughout the world. The second approach considered historical data on the seismicity of the region and the potential size of unrecognized faults in that region.

Earthquake Recurrence—Earthquake recurrence relationships express the rate or annual frequency of earthquakes occurring on a seismic source. Seismic sources generate a range of earthquake magnitudes, up to some maximum magnitude. A magnitude-distribution model defines the relative number of earthquakes having particular magnitudes. Methods for developing these relationships are usually different for fault sources than for areal sources. Experts estimated recurrence rates for fault sources from geologic data and rates for areal sources from historical seismicity data.

Vibratory Ground Motion Hazard—The level, or amplitude, of ground shaking is influenced by three main elements. The first element is how the size and nature of an earthquake controls the generation of earthquake waves. The second element is the travel path of seismic waves from the source of the earthquake to a particular site. The length of this path is important because the amplitude of ground motion will decrease (attenuate) with distance. The third element is the local site condition, or the effect of the uppermost several hundred feet of rock and soil, and the surface topography. Experts explicitly addressed all three of these elements in the Yucca Mountain seismic hazard analysis. Combining the ground motion analysis with seismic source characteristics produces a probabilistic representation of vibratory ground motion hazard that gives annual exceedance probabilities associated with different levels of earthquake ground motion.

Fault Displacement Hazard—Fault displacement hazard is the hazard related to rupture along a fault triggered by an earthquake. Based on the careful study of fault ruptures associated with earthquakes around the world, the potential for fault displacement is categorized as either principal or distributed faulting. Principal faulting occurs along the main plane of a fault. Distributed faulting is rupture that occurs on other faults in the vicinity of an earthquake in response to the principal displacement.

The DOE's method for assessing probabilistic fault displacement hazard is very similar to that for vibratory ground motion hazard and relies heavily on the detailed geologic studies of individual faults in the Yucca Mountain vicinity. Experts evaluated the fault displacement hazard at nine locations within the Yucca Mountain site. These locations span the range of known faulting conditions in the area, which include recognized faults to small fractures and unfaulted rock. For the period of repository operations (i.e., before closure of the repository surface facilities), results of the hazard assessment show that, in the areas where waste would be emplaced, fault displacements of 0.1 cm (0.04 in.) have less than one chance in 100,000 of being exceeded each year (CRWMS M&O 2000fd, Section 6.6.3). DOE studies have also shown that the consequences of fault displacement in the repository after the repository is closed will not significantly affect performance (see Section 4.3.2.2.3 for a discussion of fault displacement effects).

4.3.2.2.3 Application of Seismic Hazard Analyses

Based on the results of the probabilistic seismic hazard analyses, a team of scientists computed the vibratory ground motion inputs to be used for preclosure design analyses. These inputs were developed for the following areas:

- At the repository elevation, about 300 m (1,000 ft) below the ground surface (Point B)
- On a rock outcrop at the ground surface directly above the repository (Point C)
- Near the North Portal of the Exploratory Studies Facility, where the Waste Handling Building would be located during the preclosure period (Point D).

Analysts selected these three areas, shown in Figure 4-165, because they represent the range of locations and conditions where the potential repository's facilities would be located. The ground motion for the three areas was derived from the ground motion developed for a "reference rock outcrop" (Point A) during the probabilistic seismic hazard analysis. The ground motion at each of the three areas is different because of local site conditions. The estimated ground motion at these areas will be used in designing repository facilities and in performance assessments of the potential repository during the postclosure period. Figure 4-166 shows calculated preliminary design ground motion for the Point B and C areas only. These are defined for a probability of 1 chance in 10,000 of being exceeded each year. The design ground motion is represented by response spectra (curves) that indicate the strength of ground shaking at different frequencies of motion (frequency, in Hertz [Hz], is the number of cycles per second of a seismic wave or the vibration of a structure). The shape and stiffness of engineered structures determine which frequencies of seismic waves are important. In addition, the frequencies of strong seismic waves at a site are determined by the size of the earthquake, its distance from the site, and the physical properties of the earth between the site and the earthquake. Two design earthquake spectra are shown on each panel of Figure 4-166 because two kinds of earthquakes control the ground shaking hazard at Yucca Mountain (CRWMS M&O 1998l). The shaking hazard at moderate frequencies (5 to 10 Hz) is due predominately to earthquakes of magnitude M_w 5.5 to 6.5 within 15 km (9 mi) of the site. The shaking hazard at low frequencies (1 to 2 Hz) is due predominately to earthquakes of approximately magnitude M_w 7 and larger at a distance of about 50 km (31 mi). The sources for these larger, more distant earthquakes are the Death Valley and Furnace Creek faults. The DOE has collected additional geotechnical data to refine analyses of ground motion at the Point B, C, and D sites.

The DOE has also studied the potential effects and consequences of fault displacements associated with both known and unknown faults. Experts conducted analyses to evaluate potential effects of fault displacement on emplacement drifts and the engineered barriers in the drifts (i.e., drip shields and waste packages) (CRWMS M&O 2000fe). They also examined how fault displacement could

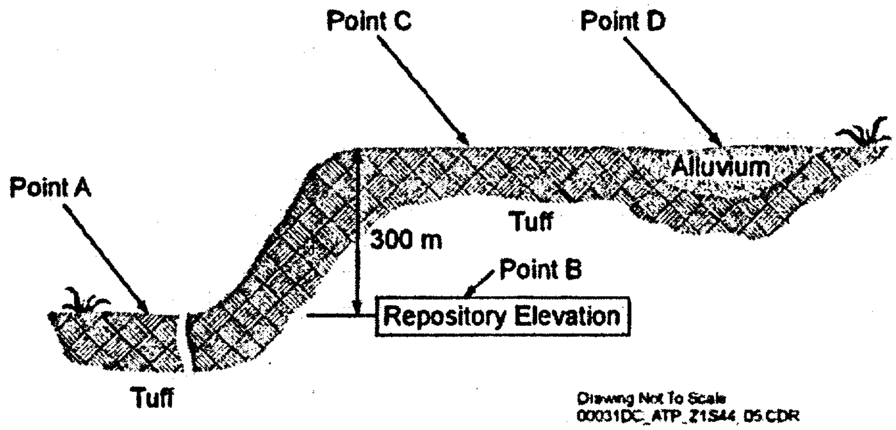

Figure 4-165. Locations of Specified Design Basis Earthquake Ground Motion Input
Point A: Reference rock outcrop at potential repository elevation (Point A is a hypothethetical site and does not correspond to an actual location at Yucca Mountain); Point B: Potential repository elevation with tuff overburden; Point C: Rock surface; Point D: Soil surface. Source: Modified from CRWMS M&O 1998l, Figure 2.3-1.

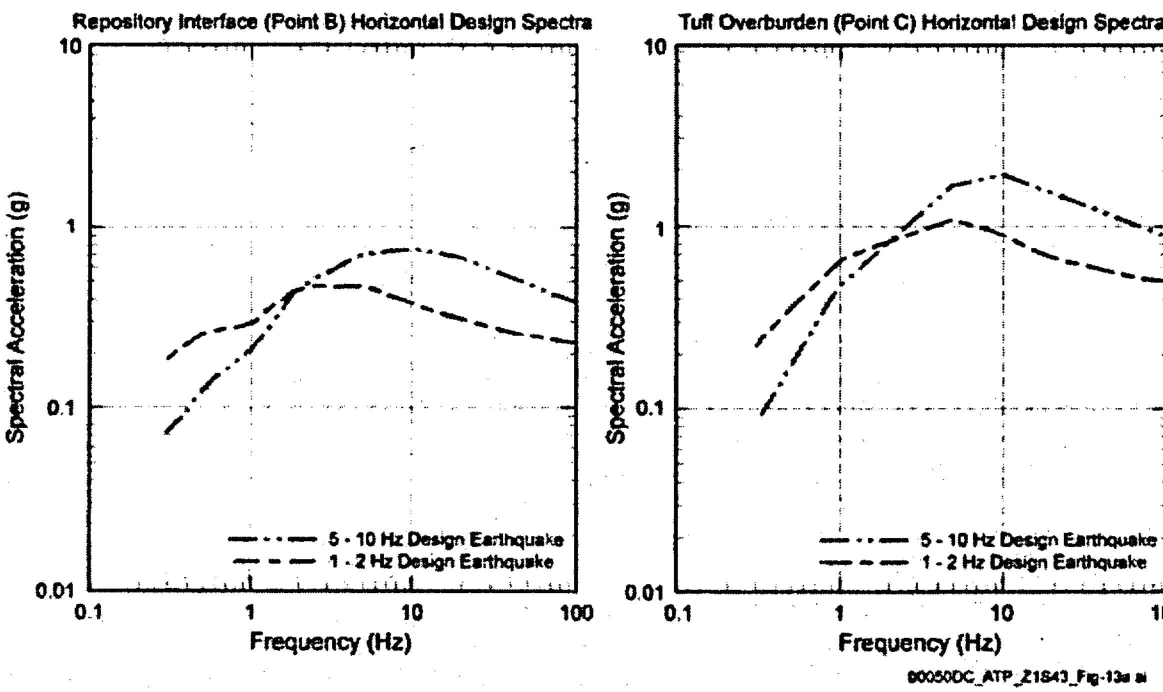

Figure 4-166. Preliminary Ground Motion Calculated by the TSPA-SR Model at Points B and C with 1 Chance in 10,000 of being Exceeded Each Year
Locations of the two points are shown in Figure 4-165. The DOE is currently collecting additional data to refine analyses of ground motion at these sites. Source: Modified from CRWMS M&O 1998l, Figures 6.2-1 and 6.2-3.

affect water movement within Yucca Mountain, which could affect the movement of radionuclides into the groundwater (CRWMS M&O 2000ff). These detailed studies show that hydrologic changes resulting from fault displacement are highly unlikely, and that faulting events will not affect the safety of the potential repository.

4.3.2.3 Human Intrusion Scenario

The DOE conducted a separate TSPA (see Section 4.4.4) to evaluate how well the repository system would limit radiological exposures under the hypothetical condition of a human intrusion. This scenario assumes a drill penetrating the repository during a possible exploration for groundwater resources. To determine the impacts from this type of disruptive event, the scenario involves site-specific data that represent the repository's natural and engineered barriers. Specifications for this scenario also include such information as the type of drilling, the size of the borehole, and the location of the borehole. By mathematically modeling this scenario, experts evaluated the repository's performance under this disrupted condition and projected the effects. This section describes the basis and assumptions for the TSPA evaluation of the human intrusion scenario.

4.3.2.3.1 Scenario Basis and Assumptions

Human intrusion analyses were performed in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a), *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Section 5.2.7), and *Total System Performance Assessment Sensitivity Analyses for Final Nuclear Regulatory Commission Regulations* (Williams 2001b).

The purpose of the TSPA for human intrusion scenario is to provide a basis for judging the resilience of the geologic repository to inadvertent human intrusion (National Research Council 1995, Chapter 4). Unlike analyses of other potential disruptive scenarios, the human intrusion scenario does not evaluate the probability of such an event occurring but instead assumes the event probability of 1. The TSPA analysis uses a "stylized" human intrusion scenario, which refers to specific characteristics that define the scenario.

The human intrusion scenario assumes:

- A single human intrusion occurs as a result of exploratory drilling for groundwater.
- The intrusion occurs some time after the repository is permanently closed.
- A drill bit penetrates a waste package and continues to the water table.
- The drillers use common techniques and practices currently used for drilling operations in the Yucca Mountain region.
- The drillers do not seal the borehole, and natural degradation processes gradually modify the borehole.
- No particulate waste material falls into the borehole.
- The analysis only considers the amount of radionuclide release that results from the intrusion.
- The analysis does not include any radionuclide releases caused by unlikely natural processes and events.

The DOE has estimated that this event could happen no sooner than about 30,000 years after closure without recognition by the driller that he had penetrated a waste package. Therefore, human intrusion is assumed to occur at 30,000 years in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Section 5.2.7). For conservatism and consistent with NRC proposed regulations, the DOE also analyzed a human intrusion scenario that assumed (TSPA-SR) that the intrusion occurs at 100 years.

For the purposes of analysis, it was necessary for the DOE to provide supplemental information and data to completely specify the human intrusion scenario. This information and data includes:

- Surface water collection and flow rate in the hypothetical borehole
- Borehole size and condition
- Type of waste exposed (e.g., spent nuclear fuel, high-level waste glass)
- Water flow conditions in the waste package
- Waste form dissolution rates
- Location of the borehole within the repository.

Therefore, all of the DOE's human intrusion scenarios assume that someone unknowingly drills for groundwater at Yucca Mountain and the drill penetrates a waste package containing commercial spent nuclear fuel or DOE high-level radioactive waste glass. The drill continues down approximately several hundred meters to the water table. The exposed radioactive waste is mobilized by degradation of the waste form and mixing with the infiltrating water, which then travels down the uncased drill hole and into the water table. After entering the water table, the radionuclides, in dissolved and colloidal forms, are transported by the groundwater to the receptor location. This scenario is illustrated in Figure 4-167.

For an intrusion at 100 years after repository closure, a waste package containing commercial spent nuclear fuel would still be thermally hot, so that any water entering the waste package would convert to vapor (CRWMS M&O 2000fg, Table 10). Thus, the absence of liquid water would prevent waste form degradation and transport of radionuclides down the drill hole. At that time, any water entering the package would convert to vapor, and the absence of liquid water would prevent the transport of radionuclides down the drill hole. However, to add a conservative bias to the analysis, the scenario does not reflect this fact and instead

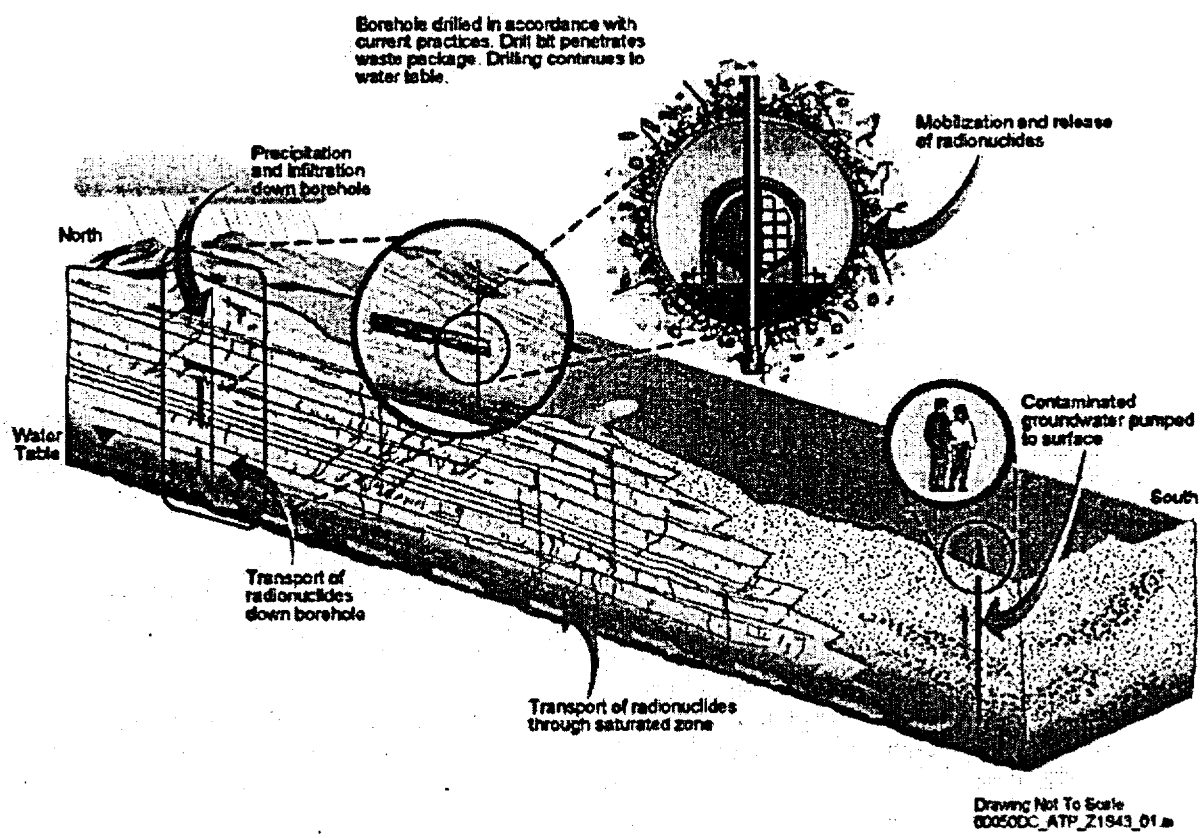

Figure 4-167. Human Intrusion Scenario

assumes liquid water flows continuously through the penetrated waste package and mobilizes radionuclides. A lower-temperature repository might not be hot enough to vaporize liquid water which then would flow continuously through the penetrated waste package. In either case, the TSPA for a 100-year intrusion would be similar. Additional specifications and assumptions for this human intrusion scenario are presented in Section 4.4.4.1.

4.3.2.3.2 Total System Performance Assessment Evaluation and Sensitivity Analyses

The TSPA-SR and supplemental TSPA evaluations and sensitivity analyses of the human intrusion scenario focused on such aspects as:

- Infiltration of water down the borehole and into the penetrated waste package
- Mobilization and release of radionuclides from a penetrated waste package
- Transport of radionuclides down the borehole to the water table
- Type and amount of radionuclides that could be transported through groundwater (i.e., water table) to the human environment
- Projected annual doses.

To compensate for uncertainty, the TSPA-SR and supplemental TSPA evaluation of the human intrusion scenario does not account for factors within the unsaturated zone (the rock between the repository and the water table) that would limit the transport of some radionuclides. The TSPA-SR evaluated the consequences of the scenario (with human intrusion at 100 years) during the remaining part of the 10,000-year compliance period following the hypothetical intrusion. The analysis assumed the same climatic and hydrogeologic conditions as the nominal scenario (i.e., the representation of the most plausible evolution of the repository system).

The TSPA-SR analysis (intrusion at 100 years after closure) focused on:

- Radionuclides with long half-lives relative to the compliance period, which will not decay away before reaching the point of compliance
- Radionuclides that are highly to moderately soluble in water (i.e., quickly mobilized after waste package failure) and nonsorbing or low sorbing (i.e., transport is minimally delayed)
- Radionuclides with the potential to produce significant radiation exposures if contacted or consumed by the group receptor
- Radionuclides in the form of tiny (i.e., approximately 0.1 to 5 μm (0.000004 to 0.0002 in.) colloidal particles that are carried at the speed of the groundwater.

The DOE performed a sensitivity analysis (see Section 4.4.5) of this evaluation to identify the factors that have the greatest influence on the release, transport, and radiation exposure to the hypothetical receptor group.

Section 4.4.4 summarizes the results of the TSPA-SR model evaluation of the 100-year human intrusion scenario. In addition, Section 4.4 of *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a) documents the results in detail. *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Section 5.2.7) summarizes the results of the human intrusion scenario occurring at 30,000 years.

4.3.3 Scenarios Addressed and Screened Out of Total System Performance Assessment

Over the past decade, scientists have hypothesized and considered many possible scenarios of conditions that could occur in the distant future and have the potential to affect the repository's capability to isolate radioactive waste. They selected the most probable of these conditions and developed scenarios for further analysis in the TSPA. Many conditions and scenarios were screened out according to probability or consequence. The technical basis for excluding these scenarios from consideration in analyses of the performance of the design described in this report is presented in the various process model and analysis model reports and in the DOE FEPs database (Freeze et al. 2001).

Two particular scenarios that the DOE considered but ultimately excluded from further TSPA analysis have been the focus of past scientific interest. They are:

1. **Rise of the water table**—a hypothesis that speculates that tectonic and hydrothermal events could cause the water table to rise to the repository level

2. **Nuclear criticality**—the possibility of the spent nuclear fuel in the repository causing a self-sustaining chain reaction (as a result of chemical or physical processes affecting the waste) either in or after release from breached waste packages.

As explained in the following sections, the DOE and others have determined that the water table rise scenario is not scientifically credible and that the nuclear criticality scenario is highly improbable. A model detailed analysis has shown that the probability of a nuclear criticality event falls below the screening threshold of less than 1 chance in 10,000 in the first 10,000 years following emplacement (see Section 4.3.3.2.3). This is primarily because there are few failures of waste packages, which are designed to prevent breach before 10,000 years. Therefore, it was screened out. However, because these scenarios have been the subject of much discussion, Sections 4.3.3.1 and 4.3.3.2 present the scientific investigations that led to the DOE's conclusions.

4.3.3.1 Long-Term Stability of the Water Table

The current elevation of the water table beneath Yucca Mountain is about 730 m (2,400 ft) above sea level, and the potential repository horizon would be an average of about 300 m (1,000 ft) above this elevation. The minimum height of an emplacement drift above the water table is about 210 m (690 ft) in the northernmost section of the repository. Geologic, geochemical, and hydrologic investigations of the site indicate that the elevation of the water table has fluctuated in the past and that the maximum elevation in the Yucca Mountain region was about 120 m (390 ft) above the current level, primarily as a result of variation in climate. Paces and Whelan (2001) have recently re-estimated the maximum climate-caused water table rise during the Pleistocene, including glacial climates, to be 17 to 30 m (56 to 98 ft). Based on this evidence and on numerical modeling, and to conservatively account for uncertainties related to future climate states, the DOE's analyses of repository performance include future variations in water table elevation of up to 120 m (390 ft). In 1987, a DOE scientist hypothesized that much larger variation in the water table could occur as a result of tectonic processes (Szymanski 1989). Szymanski (1989) postulated that tectonic stress could cause fracture apertures to be opened wider than they would be under normal stress and that during an earthquake the extensional stress could be released, causing the fracture apertures to decrease. He further postulated that, in a process called "seismic pumping," the water in the fractures would be compressed, forcing the water upward to the level proposed for storage of nuclear waste (Szymanski 1987, 1989). A group of 23 project scientists (DOE 1989) reviewed this hypothesis and concluded it was not supported by available information.

Since that initial internal review, Szymanski and colleagues have written several additional papers in support of the hypothesis that the repository could be inundated by a rising water table (Davies and Archambeau 1997a, 1997b; Dublyansky and Reutsky 1995; Hill et al. 1995). This new information has been systematically evaluated by the DOE and in a series of external peer reviews, which are discussed in this section. These external peer reviews included:

- A five-member peer review panel composed of outside reviewers convened by the Yucca Mountain Site Characterization Project, with conclusions published separately as a majority report (Powers et al. 1991) and a minority report (Archambeau and Price 1991).

- A single reviewer from the USGS, at the request of one of the members of the five-member panel (Evernden 1992).

- A 17-member panel established by the National Academy of Science/National Research Council at the request of the DOE (National Research Council 1992).

- NRC contractors at the Center for Nuclear Waste Regulatory Analyses (Leslie 1994).

- The saturated zone flow and transport expert elicitation panel (CRWMS M&O 1998j, Section 3.2.9.3).

- The Nuclear Waste Technical Review Board (NWTRB), which, through a panel of outside experts, reviewed documents in support of the upwelling groundwater model submitted in 1997 (Cohon 1998).

Except for the minority report of Archambeau and Price (1991), these reviews all concluded that the available evidence does not support the proposed upwelling groundwater hypothesis.

This section will discuss:

- Data and analyses related to the origin of mineral deposits that led to Szymanski's conclusions

- Data and analyses related to the past elevation of the water table

- Analyses of the future potential for variation in the elevation of the water table.

4.3.3.1.1 Evidence for the Origin of Surficial Deposits of Calcite and Opaline Silica

A trench, designated Trench 14, was excavated to a depth of 1.8 m (6 ft) in 1982 to study the Bow Ridge fault along the west side of Exile Hill. The trench exposed a vein-like deposit of calcium carbonate and subordinate opaline silica, as well as a breccia deposit (angular fragments of older rock cemented within a fine-grained matrix) in the bedrock on the footwall. The origin of these deposits was the subject of considerable debate, so in 1984 the trench was deepened to 3.6 m (12 ft) to help elucidate the origin of the deposits. Taylor and Huckins (1986) proposed that the deposits were formed by evaporation of precipitation, leaving behind dissolved minerals (a pedogenic, or soil forming, origin). After examination of deposits in Trench 14, Szymanski (1987) hypothesized that the potential repository was at risk because of upwelling water. Varying hypotheses on the origin of the deposits and peer reviews of the hypotheses are discussed in this section.

Field Observations—Stuckless, Peterman et al. (1992) examined several lines of evidence and concluded that a pedogenic origin provided the best explanation for the deposits observed at Trench 14. This evidence includes field relationships, such as the slope-parallel orientation and great lateral extent of the calcic or caliche deposits below the surface of soils in the desert Southwest. Additionally, some carbonate layers continue upslope beyond their supposed feeder-vein source. A second deepening of Trench 14 in 1989 showed (Taylor and Huckins 1995) that the veins pinch out with depth (Figure 4-168). In addition, the veins are not visible in the Exploratory Studies Facility where the tunnel intersects the Bow Ridge fault, although minor calcite may occur on the footwall. These observations contrast sharply with the morphology observed at Travertine Point (Figure 4-169), a site of known groundwater discharge along Furnace Creek on the east side of Death Valley.

Textural and Mineralogical Evidence—Vaniman, Bish et al. (1988) have shown that the deposit at Trench 14 is similar mineralogically and texturally to soil deposits and distinct from spring deposits. For example, the vein material in Trench 14 is poorly indurated (soft and not well cemented together), porous, and fine grained. In contrast, feeder veins, like those at Travertine Point, are coarse grained and well indurated (having a solid, hard structure). The deposit at

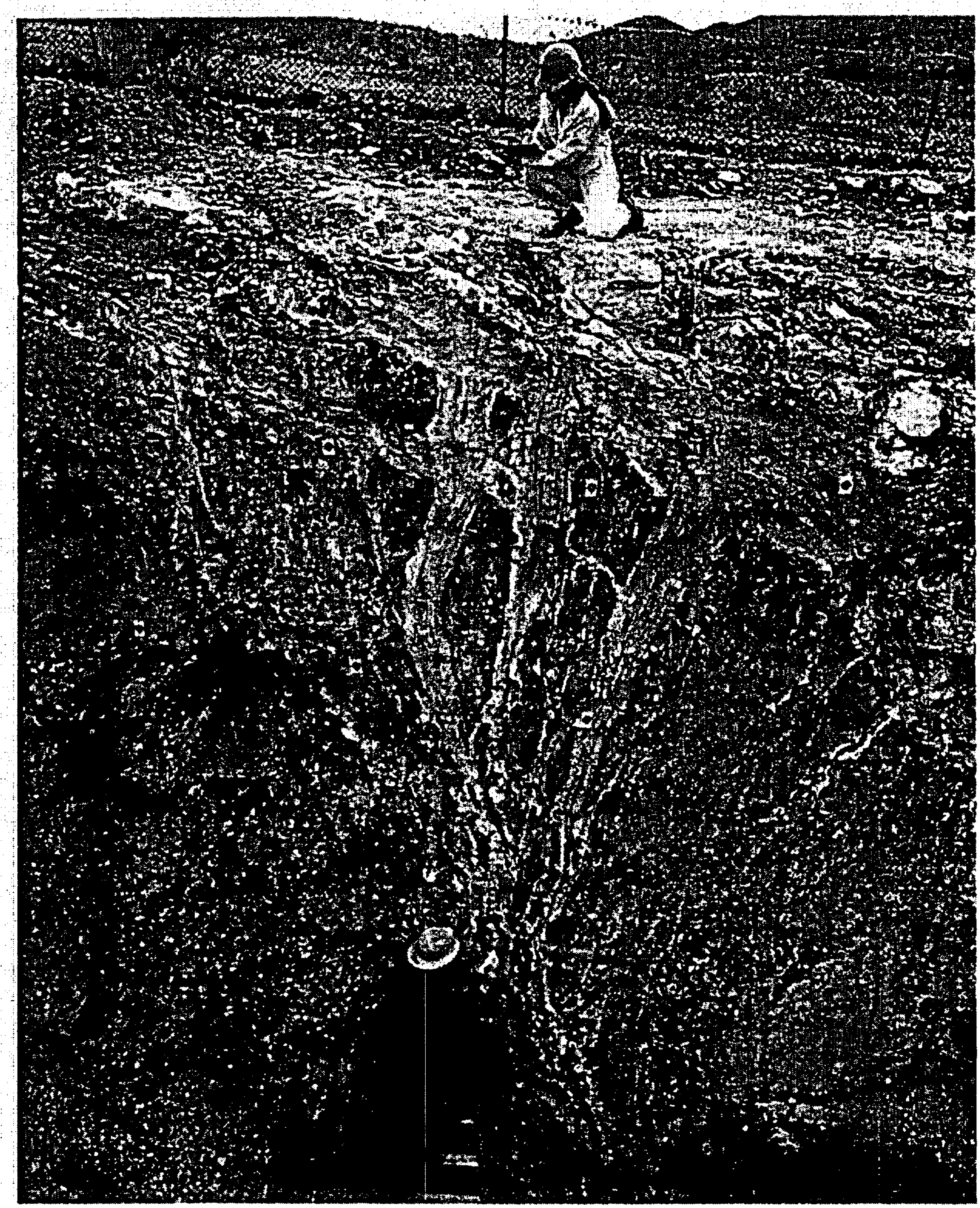

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Figure 4-168. Veins in Trench 14 Pinching Out with Depth

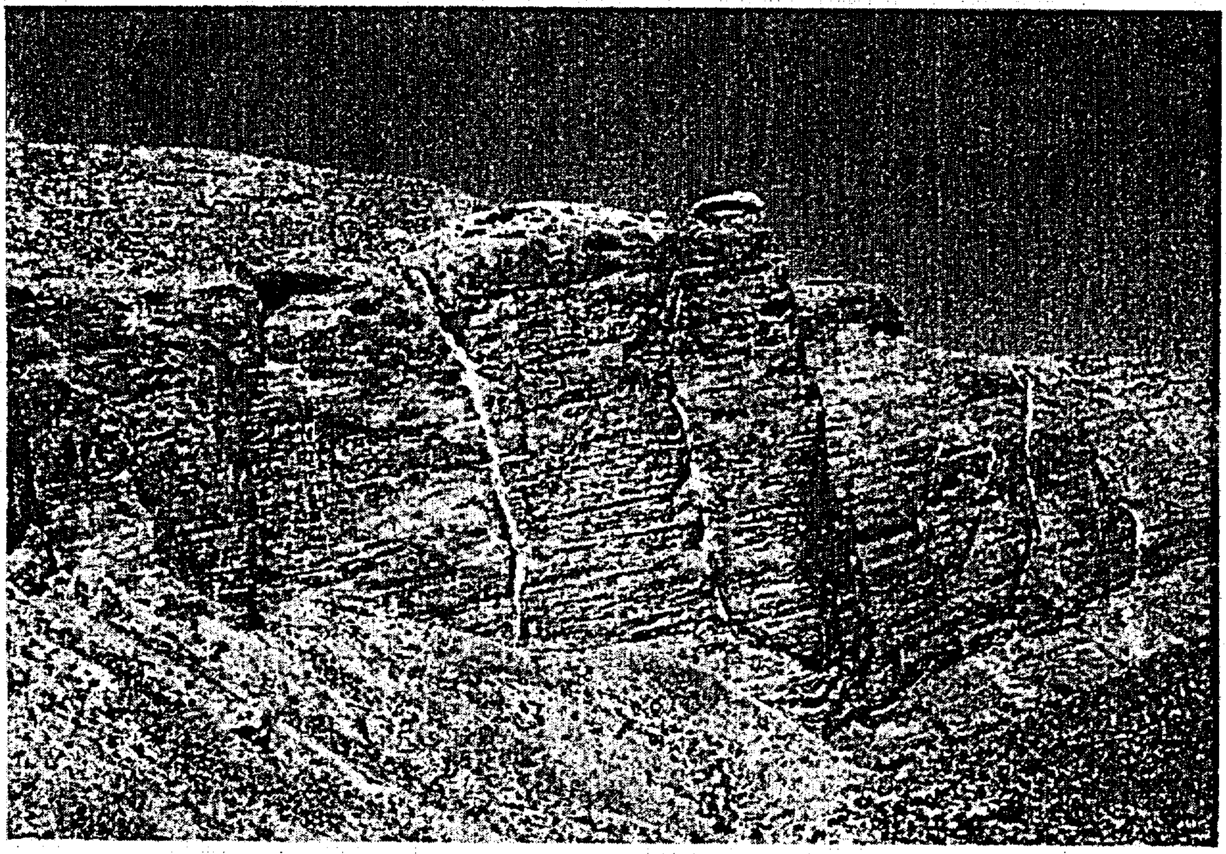

Figure 4-169. Photograph of Travertine Deposit and Feeder Vein at Travertine Point, along Furnace Creek, Death Valley, California
The leftmost vein is about 0.5 m (1.6 ft) wide.

Trench 14 exhibits intimate intergrowths of calcite and opal, as well as abundant ooids (egg-shaped particles) and pellets. Both features are atypical of any type of spring deposits, but they are common in soils. Springs and seeps have abundant biogenic evidence of their past higher water content, including fossils of aquatic animals, such as ostracodes and mollusks, and algal or diatomaceous deposits of opal-A. These biogenic features are not found at Trench 14. Biogenic evidence found at springs and seeps also includes poorly preserved root casts of phreatophytic plants (i.e., plants that obtain moisture from below the water table). In contrast, Trench 14 has well-preserved, very delicate filaments that are common in pedogenic calcretes and are associated with roots of xerophytic plants (i.e., plants adapted to low moisture conditions, typically with deep roots).

Monger and Adams (1996) examined the microscopic structure of the deposits at Trench 14 and elsewhere and compared the textures with known pedogenic and phreatic (from groundwater) deposits. They used a combination of thin sections, scanning electron microscopy, x-ray diffraction, and cathodoluminescence, and concluded that the vein deposits appear to be of pedogenic origin.

Geochemical Evidence—Vaniman, Chipera et al. (1994) note that the major- and trace-element chemistry of the deposit at Trench 14 is distinct from the chemistry of spring deposits and similar to the chemistry of soils. The iron and scandium abundance data are most distinctive. The weathering process that forms soils elevates the concentrations of these elements. The elevated iron and scandium content in the veins has the same ratio as the local soils. Lanthanum/ytterbium ratio values in the Trench 14 deposit also match those of the soils. This correspondence can be accounted for only if the material in the veins is derived from soil.

Isotopic data—Isotopes are atoms of a chemical element with the same atomic number (i.e., the same number of protons) but a different atomic mass (containing a different number of neutrons). Several types of isotopic data can be used to demonstrate that local groundwater was not involved in the formation of the Trench 14 veins. The isotopic evidence and references to isotopic work are summarized by Stuckless, Marshall et al. (1998). Oxygen isotopes in the calcite found in veins at Trench 14 indicate that their origin would have been at unreasonably low temperatures if they had been precipitated from either of the aquifers beneath Yucca Mountain. Carbon isotopes preclude involvement of the deepest groundwater aquifer at Yucca Mountain. Strontium in the vein deposit has a greater proportion of the isotope strontium-87 than strontium found in either aquifer beneath Yucca Mountain, which precludes the involvement of either aquifer in the formation of the veins. In contrast, the isotopic composition of strontium in the Trench 14 deposits is within the range measured for soil deposits, which is permissive evidence for formation of the deposits by soil-forming processes. The uranium-234/uranium-238 activity ratio in groundwater beneath Yucca Mountain is anomalously large relative to most groundwaters (greater than 5 in the volcanic aquifer). In comparison, the uranium-234/uranium-238 activity ratio values for both soils and the calcite from Trench 14 are less than 1.5. This isotopic system again shows that the local groundwater could not have formed the deposits, but that they may be closely related to soil-forming processes. Finally, lead isotope data also support a pedogenic origin for the calcite and identify a detrital origin as the probable source of the lead.

Radioactive elements decay at known rates, so the relative abundance of radioactive elements and their decay products can sometimes be used to determine the age of a sample. Alternatively, if one knows the amount of a radioactive element initially present, one can measure the amount currently remaining to calculate an age. Carbon-14 dating is an example of the latter. Samples of modern groundwater from volcanic tuffs sampled within 1 km (0.6 mi) of the potential repository block have apparent carbon-14 ages of 12,000 to 18,500 years (Benson and McKinley 1985). In contrast, apparent thorium-230/uranium-234 ratio ages of calcite found at Trench 14 range from about 80,000 to more than 400,000 years. Data from a drill hole into calcite at Devils Hole (a fault-controlled cavern in limestone in Ash Meadows) show little variation in the isotopic composition of strontium, uranium, oxygen, and carbon for the last 500,000 years (Stuckless, Peterman et al. 1992; Ludwig, Simmons et al. 1992; Winograd et al. 1992). Because the isotopic composition of groundwater beneath Yucca Mountain has not likely varied significantly during the last 500,000 years, the comparison of modern groundwater with that of the deposits provides a valid means of assessing the origin of the deposits.

4.3.3.1.2 Peer Reviews and Evaluations of New Evidence

In 1990, the DOE requested that the National Academy of Sciences/National Research Council consider whether the water table had risen in the geologically recent past to the level of the potential repository and whether a water table rise was likely to occur over the life of the repository in the manner proposed by Szymanski (1989). The National Research Council established a panel that reviewed the pertinent literature and data available up to 1992. This panel consulted with scientists involved in related field and laboratory studies. The panel's conclusion (National Research Council 1992, p. 3) was that none of the evidence offered as proof of groundwater upwelling in and around Yucca Mountain could reasonably be attributed to that process. Furthermore, the panel stated (p. 130): "The preponderance of features [ascribed to ascending water] (1) were clearly related to the much older (13-10 Ma) volcanic eruptive processes that produced the tuffs in which the features appear, (2) contained contradictions or inconsistencies that made an upwelling groundwater origin geologically impossible or unreasonable, or (3) were classic pedogenic features recognized worldwide." The panel concluded that the physical and textural evidence from the veins in the trenches indicated a sedimentary, low-temperature origin from descending meteoric water (infiltration) rather than an origin involving upwelling of thermal water from deep within the crust. The panel also concluded (p. 56): "...to date the preponderance of evidence supports the view that the calcretes and other secondary carbonates in veins of the area formed from meteoric water and surface processes."

Other independent reviewers reached similar conclusions, which were considered by the National Research Council. In the majority report of the independent peer review panel convened in 1991, Powers et al. (1991, p. s-2) concluded: "Surficial deposits cited by Szymanski as evidence of upwelling fluids are consistent in isotopic and physical character with surficial, pedogenic processes; these deposits are not consistent isotopically with known groundwater in the area of Yucca Mountain." Although Archambeau and Price (1991), in their minority report, supported Szymanski's hypothesis, a colleague they selected to review their report concluded the model was "a set of unsupported and unsupportable assertions" (Evernden 1992, p. 65).

After the National Academy of Sciences/National Research Council reached its conclusions, Szymanski and others, as documented by Hill et al. (1995), asserted in 1995 that much of the data available for the calcite/opal deposits could be explained by the upwelling of warm, carbon dioxide-rich water along faults. Hill et al. postulate that once this upwelling water reaches the surface, it flows downhill back into the ground. Therefore, they argued, the resulting deposits are slope-parallel and acquire a pedogenic character. In a critique of this hypothesis, Stuckless, Marshall et al. (1998, p. 70) concluded the hypothesis was based on misstatements, omissions of available information, and misleading generalizations that lead to an erroneous conclusion. In addition, Vaniman, Carey et al. (1999) have examined the chemistry of zeolitic strata beneath the potential repository horizon and concluded that flow in the unsaturated zone has been downwards and predominately gravity-driven for the last 12 million years.

The NWTRB (Cohon 1998) reviewed a group of reports submitted by the Nevada Nuclear Waste Project Office. One of the reports cited evidence from fluid inclusion studies that the authors asserted were an indication of a purported high-temperature origin for secondary calcite collected in the Exploratory Studies Facility (Dublyansky and Reutsky 1995). However, the age of the secondary calcite was unknown, and there was a well-documented thermal period that affected the volcanic rock for a long time after its formation. Because of this and other evidence from the Exploratory Studies Facility excavation, discussed below, the NWTRB concluded that the fluid inclusion data does not significantly affect the conclusions of the National Academy of Sciences/National Research Council report (National Research Council 1992). The NWTRB did, however, recommend further studies of this type in conjunction with age determinations.

In response to this recommendation, the DOE sponsored research at the University of Nevada, Las Vegas and the USGS on age and thermal history indicated by fluid inclusions. Representatives of the state of Nevada participated in the sampling program and were given splits of all materials collected. In addition, the representatives participated in biannual meetings to review and interpret the data. The general conclusion reached by USGS and University of Nevada, Las Vegas researchers was that the fluid inclusions formed in the vadose environment by downward percolating meteoric water and that the environment was warmer than ambient until at least 5 million years ago; however, there is no evidence for above-ambient temperature precipitation during the last 1.9 million years (Paces, Whelan et al. 2000; Paces, Neymark, Persing et al. 2000; Whelan, Roedder, Paces, Neymark et al. 2000; Wilson, N.S.F., Cline, Rotert, and Amelin 2000; and Wilson, N.S.F., Cline, and Amelin 2001).

Evidence for precipitation in a vadose environment includes (1) only 1 to 40 percent of the cavities are mineralized in a given area, whereas precipitation in a saturated environment would predict that most, if not all sites would be mineralized (Marshall, Neymark et al. 2000); (2) mineralization is restricted to floors of cavities and footwalls of fractures (Marshall and Whelan 2000); and (3) the fluid inclusion assemblage of all liquid, all vapor, liquid and vapor in variable proportions is most consistent with a vadose environment (Whelan, Roedder, Paces, Neymark et al. 2000).

Fluid inclusion temperatures for all but the earliest calcites range from 35° to 75°C (95° to 167°F) (Whelan, Roedder, Paces, Neymark et al. 2000; Wilson, N.S.F., Cline, Rotert, and Amelin 2000). Most of these temperatures were determined for calcite that is clearly older than 4 to 5.3 million years (Wilson, N.S.F., Cline, and Amelin 2001). The chemical composition of calcite changed between 2.8 and 1.9 million years ago to include a few percent magnesium, and this calcite lacks two-phase inclusions, thereby indicating precipitation at ambient temperatures (Wilson, N.S.F., Cline, and Amelin 2001).

The isotopic composition of strontium in secondary calcite collected in the Exploratory Studies Facility is more radiogenic (containing more of the isotope strontium-87) in successively younger layers, which is consistent with an origin of meteoric water reacting with rocks that are getting older and accumulating radiogenic strontium (Marshall and Whelan 2000). Carbon isotopes also show an evolution in time that can be related to a change in plant community at the earth's surface, which in turn reflects changing climate (Whelan and Moscati 1998). In contrast to evidence for downward percolating water, groundwater beneath Yucca Mountain is undersaturated with respect to calcite and could not precipitate that mineral without significant degassing or evaporation.

Considerable geochronology has been done on the secondary minerals. Uranium–lead dating shows a long-term slow average growth rate, which is consistent both for an entire secondary mineral coating or for parts of a coating where layers of opal are separated by calcite (Neymark et al. 1998). Uranium series dating yields similar growth rates for the outer layers of secondary minerals (Paces, Whelan et al. 2000; Paces, Neymark, Persing et al. 2000). Disagreement in apparent ages between techniques with different half-lives and the correlation between initial uranium-234/uranium-238 and apparent age is best explained by a continuous growth model and slow growth rates (Neymark et al. 1998; Neymark and Paces 2000).

4.3.3.1.3 Evidence Related to Past Water Table Elevation

Field Observation—Although the calcite and opaline silica deposits provide no direct information on past water table elevations, estimates can be made from other evidence for former high levels of the water table in the region surrounding Yucca Mountain during the past 2 million years. The evidence includes:

- Tufas and travertines
- Calcitic veins and calcite-lined tubes that mark the routes of former groundwater flow to springs
- Former water levels marked by calcite cave deposits on the walls of Brown's Room within Devils Hole
- Widespread marsh deposits (composed of silty marls, diatomaceous earth, and clays) formed from past groundwater discharge.

Most of these features are attributable to the carbonate aquifer, which is the deep and probably confined aquifer beneath Yucca Mountain. Nonetheless, this aquifer and the one hosted by the volcanic rocks and valley fill likely have responded similarly to past conditions. Available evidence indicates (1) an apparent lowering of the water table of 50 to 70 m (160 to 230 ft) for the carbonate aquifer in the east-central Amargosa Desert since the middle Pleistocene and (2) an apparent lowering of perhaps as much as 130 m (430 ft) since the end of the Pliocene. This estimated general lowering does not preclude small water table fluctuations in response to climate changes superimposed on the general trend.

There are also several discharge deposits from the volcanic and valley-fill aquifer, including three small deposits near the south end of Crater Flat. Root casts from these deposits have yielded uranium-series ages of approximately 10,000 to

20,000 years (Paces, Mahan et al. 1995). Four carbon-14 ages for root casts range from approximately 6,000 to 16,000 years and confirm the young (and possibly Holocene) age for groundwater discharge in Crater Flat. The initial uranium-234/uranium-238 ratio values and the initial strontium-87/strontium-86 values (Marshall, Stuckless et al. 1993) agree with the values obtained for samples from the volcanic and valley-fill aquifer in Crater Flat (Ludwig, Peterman et al. 1993; Peterman and Stuckless 1993). This correspondence confirms the origin of the Crater Flat deposits as groundwater discharge from a regional aquifer.

The largest and most extensive past discharge site for the volcanic and valley-fill aquifer is near Stateline, Nevada. This site is particularly significant in that it occurs where the regional groundwater flow model predicts that—under conditions of nearly a 15-fold increase in recharge and a water table rise of about 100 m (330 ft) beneath Yucca Mountain—discharge would occur (Czarnecki 1984); note that the amount of water table rise predicted to initiate spring discharge is less than the conservative, maximum water table rise calculated by Czarnecki and discussed in Section 4.3.3.1.4. Eight uranium-series ages on five different samples from this site range from approximately 11,000 to 110,000 years, but the ages cluster around the times of the last two pluvial periods (times with higher rainfall) (Paces, Neymark, Marshall et al. 1996). This suggests that maximum water table rises correspond to the wettest past climates. Recent work by Paces and Whelan (2001) on spring discharge deposits from Nye County Early Warning Drilling Program wells is interpreted to indicate that the maximum Pleistocene groundwater table rise was only 17 to 30 m (56 to 98 ft).

Devitrification and Other Mineralogical Evidence—The maximum water table rise suggested by past discharge deposits south of Yucca Mountain is supported by data from drill holes at Yucca Mountain. Bish and Vaniman (1985) noted that the volcanic tuffs were devitrified (i.e., glass was altered to minerals) below the current water table and for as much as 80 to 100 m (260 to 330 ft) above that surface. Devitrification is attributed to prolonged contact with water; therefore, the top of the devitrified zone marks the high stand of the water table. Dibble and Tiller (1981) have concluded that the time required to form zeolites from glass is on the order of 10,000 years, so larger short-term fluctuations are not precluded by the elevation of devitrified tuff. This suggests that the water table must have remained about 100 m (330 ft) higher than at present over the thousands of years required for zeolitization of the glassy tuffs (NRC 1999b, pp. 27 and 28).

Levy (1991) reevaluated the base of the vitric tuff as an indicator of the hydrologic past, considering structures and uplift occurring after devitrification. She noted that the uppermost boundary of the devitrified tuff, which occurred farthest above the current water table, was not parallel to the water table, suggesting that it formed before tilting of the tuffs. Therefore, at least some of the devitrification must have occurred more than 12 million years ago. The most recent water level fluctuations would postdate major tectonic events, but would be difficult to date. The base of the vitric tuff shown on Bish and Vaniman's (1985) cross sections is 10 m (33 ft) to more than 100 m (330 ft) below the base of the potential repository horizon. Thus, it appears likely that the maximum water table elevation is well below the potential repository. If the structural interpretations proposed by Levy (1991) are taken into account, the maximum past rise in the water table, for enough time to cause devitrification, was about 60 m (200 ft).

Because the shallow groundwater beneath Yucca Mountain is undersaturated with calcite, calcite can dissolve in the groundwater. Consequently, secondary calcite is rare below the current water table, occurring only where it is armored, such as in a tightly sealed fracture. Secondary calcite is also rare in a zone as much as 85 m (280 ft) above the water table (Marshall, Stuckless et al. 1993), suggesting that the water table could have risen as much as 85 m (280 ft) in the past.

Carbon isotopes in unsaturated zone calcite are consistent with the carbon isotopic signature acquired in the soil zone by downward percolating water (Marshall, Whelan et al. 1992). This consistency is also corroborated by strontium isotopic compositions for calcite and pore water that are closely similar to values in the soil zone at shallow depth and become more similar to values for the volcanic rock as water reacts with the rock during downward percolation (Marshall, Futa et al. 1998).

Evidence from the Exploratory Studies Facility Excavation—Studies of secondary minerals from the Exploratory Studies Facility show that these minerals formed in the unsaturated zone (Paces, Neymark, Marshall et al. 1996). For example, mineralization in the Exploratory Studies Facility is found only on the floors of cavities and footwalls of open fractures, which contrasts with the locus of mineralization for geodes or veins that formed in the saturated zone. Most cavities are devoid of the mineralization that would be expected in a saturated environment. Uranium–lead and uranium-series dating have shown that the environment of deposition for the secondary minerals has stayed the same for millions of years (Neymark et al. 1998; Neymark and Paces 2000).

4.3.3.1.4 Future Water Table Elevations

Although nothing in the geologic record suggests that the water table might rise sufficiently to flood the potential repository horizon, there are two general mechanisms proposed as capable of doing so in the future: climate change and tectonic activity. A careful examination of both of these mechanisms shows that neither is likely to be able to cause flooding of the repository level.

The long-term climate history has been examined and correlated with variations in the Earth's orbit over the past 400,000 years (USGS 2000a). This climate study concluded that most of the next 10,000 years will be wetter, cooler, and more like the glacial periods in the past and that the climate will be much like the current climate in northern Nevada. Czarnecki (1984) modeled the regional groundwater flow system to examine water table rises due to increased precipitation (i.e., pluvial periods). He calculated a maximum increase in water table altitude of about 130 m (430 ft) beneath the emplacement horizon. This analysis is considered conservative because a 100-percent increase in precipitation during pluvial periods was assumed. This in turn results in a 15-fold increase in recharge from the assumed modern rate of 0.5 mm (0.02 in.) per year to about 8 mm (0.3 in.) per year at Yucca Mountain. Half of the calculated recharge flux in the model was applied directly east of the potential repository site, along a segment of Fortymile Wash, which is consistent with the proposal of Claassen (1985) that Fortymile Wash is an area of recharge under wetter climatic conditions. The flux at Fortymile Wash causes about three-quarters of the computed water table rise of 130 m (430 ft). Czarnecki (1984) notes, however, that under a 100-percent increase in precipitation, large quantities of runoff might flow away from the area down Fortymile Wash and other drainage ways. This would have the effect of decreasing the effective groundwater recharge to less than the calculated values.

Based on past discharge deposits, Quade et al. (1995) calculated a maximum past water table elevation. They concluded that the maximum increase in water table elevation under Yucca Mountain in response to climate change was less than or equal to 115 m (380 ft) during the last full glacial period. They estimated the paleo-water table rise at the Lathrop Wells diatomite spring deposits based on water table information from Winograd and Thordarson (1975). The rise of 115 m (380 ft) was needed to establish spring flow in the past. Nye County drilling at these spring deposit sites established that the water table is currently about 16 to 30 m (52 to 98 ft) below the land surface (NRC 1999b, pp. 25, 26, and 31). This 115 m (380 ft) value is now recognized as a significant overestimate. Recent work by Paces and Whelan (2001) on results from the most recent Nye County drilling indicates that the maximum water table rise during the Pleistocene was between 17 to 30 m (56 to 98 ft). Thus, multiple lines of evidence suggest that a 120-m (390-ft) rise in water table elevation is a reliable estimate of the potential maximum increase due to climate change, based on a projected wetter future climate (CRWMS M&O 2000c, Section 3.7.5.2). Future climate changes are not expected to cause the emplacement drifts to flood because they would be located at a distance ranging between approximately 210 m (690 ft) and 390 m (1,300 ft) above the water table. The average distance of the repository above the water table would be about 300 m (1,000 ft).

Possible tectonic-induced changes in water table elevation include volcanic and seismic effects. If basaltic intrusion formed barriers downstream from Yucca Mountain, those barriers could raise the elevation of the water table, much like a dam impounds water. Similarly, a dike that is formed upgradient from the repository could lower the water table at Yucca Mountain. The heat associated with a volcanic intrusion could also cause the water table to rise. However, the only potential volcanism near Yucca Mountain would be basaltic dikes that tend to form along faults in extensional tectonic areas and are typically less than two, but potentially up to four, meters in width (Carrigan, King, and Barr 1990). Thus, future intrusion would be expected to be small and to trend in a northerly direction, which coincides with the principal strike of faulting. Movement of groundwater at Yucca Mountain is parallel to the direction of possible dike formation, so an intrusive dike would be unlikely to form a barrier to flow. As described previously, Szymanski (1989) and Archambeau and Price (1991) have postulated seismic activity as a driving mechanism to raise the water table to the level of the potential repository. Carrigan, King, Barr, and Bixler (1991) and the National Research Council (1992) examined this mechanism and concluded that it would not raise the water table more than a few meters. In fact, the opposite effect is more common. Increased stream flow and decreased wellheads have been observed after moderate earthquakes (Rojstaczer and Wolf 1992; National Research Council 1992).

Davies and Archambeau (1997a, 1997b) developed a variation of the seismic pumping model. Their model posits that variations in the state of stress cause changes in water table elevation and that these changes may be as great as several hundred meters. The NWTRB asked an independent expert to review this hypothesis and other material. The reviewer concluded, "The interpretations depend significantly upon theoretical models that have never been tested or previously used and run counter to observations in nature and in the laboratory" (Rojstaczer 1998; see also Rojstaczer 1999). Based on this review, the Board concluded that the material reviewed: "...does not make a credible case for the assertion that there has been ongoing, intermittent hydrothermal activity at Yucca Mountain or that large earthquake-induced changes in the water table are likely at Yucca Mountain. This material does not significantly affect the conclusions of the 1992 NAS report" (NWTRB 1999a, p. 20).

4.3.3.1.5 Conclusion

Despite the suggestion that the water table could rise to the level of the potential repository, the preponderance of evidence shows that the water table has not risen to this level in the past and is not likely to do so in the future. Earthquakes are known to have an impact on the water table, but water table excursions are likely to be small and short-lived. For these reasons, tectonically induced fluctuations of the water table have not been included in the TSPA-SR. Future, wetter climates have the potential to cause the water table to rise to levels that were experienced during past, wetter climate periods. Multiple lines of evidence suggest that 120 m (390 ft) is a reliable estimate of the potential increase in water table elevation for a future, wetter climate (CRWMS M&O 2000c, Section 3.7.5.2). Paces and Whelan (2001) estimate that the maximum water table rise during the Pleistocene was only 17 to 30 m (56 to 98 ft). Future climate changes are not likely to result in flooding of the waste emplacement drifts due to a water table rise because the emplacement drifts would be located a distance above the water table ranging between approximately 210 m (690 ft) and 390 m (1,300 ft) (see Figure 1-13 in Section 1). At the northernmost end of the repository block, the design described in this report has portions of the layout outside the emplacement area that would be less than 120 m (390 ft) above the water table. The repository layout shown in Figure 1-13 includes a ramp at the northernmost areas that serves as an access to an observation drift located below the emplacement area (see Figure 2-38 in Section 2.3.1 for labeled repository components). Sections of that ramp and the east repository main north extension that it connects to are located such that portions of the excavations could be flooded if the water table rose as much as 120 m (390 ft). Water would not be expected to flow to the emplacement drifts. Future assessment of performance and design work will consider this situation, together with more specific details of the water table and its potential rise, and ensure that the design is developed to take advantage of opportunities to contribute positively to performance. Variation in the water table caused by climate is included within the nominal dose for the TSPA-SR.

4.3.3.2 Nuclear Criticality

This section describes the FEPs that could lead to a nuclear criticality event, together with the possible consequences. It begins with a discussion of the physics of nuclear criticality, followed by a brief summary of the methods used to evaluate the postclosure criticality potential of the waste forms that may be emplaced in the potential repository. These methods ensure that all the critical configurations that could result from the degradation of the waste forms are identified and the results quantified. Criticality control is an important objective of waste package design because a criticality event can result in an increased radionuclide inventory, potentially increasing the radiation dose to the receptor. For the 10,000-year period after disposal, nuclear criticality is screened out from the TSPA nominal case analysis based on its low probability. Nevertheless, because of significant interest in this topic, the DOE investigated the potential consequences of a criticality event. The results of the investigation indicate that a nuclear criticality would not have a significant impact on repository performance.

4.3.3.2.1 Physics of Nuclear Criticality

Nuclear fission is the splitting of an atomic nucleus by an impacting neutron. Only certain isotopes of very heavy elements can be split; the most commonly known of these are the uranium-235 and plutonium-239 isotopes. The nucleus of each element has a constant number of protons but may have a varying number of neutrons; these variations identify isotopes of an element.

The key factors associated with the potential fissioning of a nucleus are the energy or speed of the impacting neutron and the characteristics of the nucleus, which affect the manner in which it reacts to the neutron. The nuclear reaction most important for criticality occurs when a nucleus absorbs a free neutron, creating an unstable compound nucleus. The compound nucleus splits into fission fragments (lighter elements), releases energy in the form of gamma rays, and emits two or three additional neutrons in the process. The released neutrons are free to collide with other nuclei, which may absorb one of them and fission as well (Duderstadt and Hamilton 1976, Chapter 2).

There are other possible outcomes from a neutron interacting with a nucleus besides fissioning. The neutron may simply collide and be scattered, transferring kinetic energy to the nucleus in the process, or it may be absorbed by the nucleus without fissioning. The likelihood of any of these interactions depends heavily on the energy of the neutron. Neutrons emitted from fission have high energy. However, the likelihood of an interaction resulting in fission increases as the energy of the neutron decreases. As a result, fission is more likely if the energy or speed of a neutron is reduced.

Each time a neutron collides with a nucleus but is not absorbed, it loses energy, its speed decreases, and its potential for fissioning a nucleus increases. This slowing down of energetic neutrons is referred to as moderation; the material that provides the nuclei that cause this slowing down is called a "moderator." In general, the lighter the element, the better it works as a moderator because it scatters neutrons much better than it absorbs them. Hydrogen, the lightest element, is a very efficient moderator. Since water contains hydrogen nuclei, it also is a very effective moderator. The silicon in sand and rocks, such as those at the potential repository site, can also serve as a moderator, but silicon is a much less efficient moderator than water.

A nuclear chain reaction can be initiated once a neutron interacts with a fissile isotope, inducing it to fission. This releases additional neutrons that are, in turn, available to cause more fissions. Of the neutrons resulting from each fission, some will be absorbed in a nucleus without a resulting fission, some will escape from the system before colliding with a potentially absorbing nucleus, and some will be absorbed and cause fission. When each fission releases just enough neutrons to cause one additional fission, the effective neutron multiplication factor (k_{eff}) equals one, the chain reaction becomes self-sustaining, and the system is considered critical.

For a nuclear criticality to occur, there must be the proper combination of material and geometric configuration, known as the critical mass and critical geometry. Fissile material is essential for criticality. The only naturally occurring fissile isotope is uranium-235. However, it is not the only isotope that can support a critical reaction. Uranium-233 and plutonium-239 can also support criticality; these isotopes are produced in a reactor by fast neutrons that are absorbed by thorium-232 and uranium-238, respectively. In general, the greater the amount of fissile material, the more likely it is to have a criticality. The presence of neutron absorbers—materials that absorb neutrons without causing fission—is also important. The greater the amount of neutron absorber material, the less likely it is to have a criticality. Isotopes of boron and gadolinium are good neutron absorbers.

The geometrical arrangements of the fissile material and any neutron-absorbing material are of equal importance in determining whether an accumulation of a fissile material can achieve criticality. Because neutrons can leak out of a system without causing fission, the most efficient geometry for the occurrence of criticality is a sphere, which has the least surface area per unit volume of any shape.

With the presence of moderating materials like water, the likelihood of fission can be greatly increased, and a reduced amount of fissile material is necessary to form a critical mass. However, criticality is possible without the presence of a moderator. These situations are known as fast criticalities because they can occur in the presence of predominantly high-energy neutrons.

In addition to the release of energy and additional neutrons, the fission process effectively removes fissile nuclei from the system by splitting them into other, lighter elements. This is referred to as fuel depletion, or burnup. Also, many of the fission products—the lighter elements resulting from the fragmenting of nuclei—are strong neutron absorbers. Their existence in the area where the critical reaction is ongoing dampens the reaction. Thus, as commercial spent nuclear fuel is depleted, its ability to support a criticality is reduced from the combination of the removal of fissile material and the creation of materials that absorb neutrons through the fission process. This is the primary reason fuel is discharged from operating reactors after several years: it can no longer effectively support a critical reaction. Incorporating fuel depletion in the criticality evaluation of systems is called "burnup credit."

A repository would contain fissile material, mostly from commercial spent nuclear fuel in the form of a reduced amount of uranium-235 (compared to what was initially loaded into the reactor) and plutonium-239. Moderating materials, primarily consisting of silicon dioxide, would be present; some water may be present as well. As a result, a criticality event is possible: (1) inside one or more degraded waste packages; (2) in the rock surrounding the emplacement drifts, as a result of water transporting fissile materials from degraded waste packages; or (3) in the rock at some distance from the emplacement drifts as a result of an accumulation of fissile materials under favorable conditions in the nearby rock. An example of the last situation would be a deposit of organic material, which could accumulate dissolved fissile material from a flow of water that had originated in or previously passed through the repository area. The probability of a criticality depends on the probability of occurrence of three conditions: (1) a waste package breach, (2) the separation of the neutron absorber from the fissile material, and (3) the presence of sufficient amounts of a moderator. The spacing between fuel rods will affect the probability of criticality for certain waste forms.

If a critical event were to occur in a repository, the characteristics and consequences of the event may be considered as falling into two categories: steady-state and transient.

In a steady-state criticality, the reaction remains constant, with the k_{eff} equal to one. The magnitude of this type of criticality is limited by the fact that the energy released as a result of the criticality serves, in part, to evaporate surrounding water. Since the water is necessary for moderation of the neutrons, removing the water through boiling restrains the reaction and would, over time, make the system no longer critical.

One of the principal consequences of a steady-state criticality would be an increase in radionuclide inventory, particularly in fission products and actinides (i.e., elements heavier than uranium, formed primarily from the initial absorption of neutrons by uranium-238 for those waste forms which contain a significant fraction of this isotope). Another result would be the production of heat from the fissioning of nuclei, which would incrementally increase the heat generated from the ongoing decay of fission products already present in the waste. The additional heat could create localized hot spots in the repository, potentially affecting nearby geochemical and other conditions. These changes could marginally affect the amount and rate of release of radioactive materials from the repository. However, evaluations have shown that neither the inventory increase nor the thermal effects are significant enough to adversely impact repository performance (CRWMS M&O 1998m, Sections 9 and 10).

A natural analogue for steady-state criticality is the family of natural reactors that occurred in a sedimentary formation approximately 2 billion years ago at Oklo, a site in what is now Gabon, Africa. These natural reactors occurred in several closely linked, very rich uranium ore bodies that were saturated with water, which served as a moderator. Criticality at Oklo continued periodically for approximately one million years, pausing when the heat from the reaction evaporated the water and resuming when the site reflooded. Such a natural reactor was possible because, two billion years ago, the natural enrichment of uranium was greater than 3 percent (by weight) (enrichment is the percentage of uranium-235 by weight contained in the total uranium content). The radioactive decay process of uranium-235 has since dropped the worldwide natural uranium enrichment from greater than 3 percent at that time to its current value of 0.72 percent. The natural reactors at Oklo at that time period are unique; no other place in the world has been found where natural reactors existed (Smellie 1995). A reactor like the one that occurred at Oklo is not probable in a repository at Yucca Mountain because (1) the prevailing geochemical conditions for the Oklo deposit allow a higher concentration of uranium than any known deposit in the world, while the geochemistry and lithology characteristics of the Yucca Mountain site are not conducive to such concentrated accumulations of fissile materials, and (2) the effective enrichment (uranium-235 plus plutonium-239) of most commercial spent nuclear fuel that would be emplaced in the potential repository is less than the enrichment of the Oklo reactors during the time they were critical (Smellie 1995).

Transient criticalities could occur if there were a sudden change in the geometry or material composition of a disposed waste. A transient criticality would increase the rate of fission rapidly so that a very large burst of neutrons would be produced for a brief period; the accompanying increased rate of energy release could lead to a large increase in pressure and temperature. A transient criticality ends when the neutron multiplication factor decreases below unity, usually because of the loss of the moderating effects of water, which boils off during heightened temperatures. If some water were to return (recharge) after the criticality ended, it could increase neutron moderation, and the critical reaction could start again. However, the recharge of water would require a relatively long time compared with the duration of the criticality, so the total radionuclide increment from a transient criticality would be much smaller than the total for a steady-state criticality enduring over the same total elapsed period. The potential for damage to waste packages in the repository because of the peak temperature pulse from a transient criticality has been investigated, and evaluations (as presented in Section 4.3.3.2.3) indicate that such effects are not sufficient to significantly alter repository performance (CRWMS M&O 1999q).

A special subset of transient criticality is autocatalytic criticality, which is a transient criticality where the usual mechanisms that tend to shut down a criticality, such as the loss of moderator or loss of confinement, are delayed until a high fission rate is achieved. Although the probability of occurrence of an autocatalytic criticality at the potential repository is so low as to be considered not credible (Paperiello 1995), it is addressed for completeness and for evaluation of any hypothetical consequences. Scientists have pointed out that an autocatalytic criticality could occur when silica is the primary moderator (Bowman and Venneri 1996), but this would require extraordinarily unusual conditions that cannot occur in the waste package or at all outside the waste package unless (1) the entire fissile content of the waste package is spread uniformly in a nearly spherical shape or (2) fissile material from multiple waste packages accumulates in a small region of rock. Either configuration is essentially impossible to achieve. If such an event were to occur, it could create a much higher peak temperature and pressure than would result from transient criticality. If such an event were to result in a large and rapid release of kinetic energy, it could be considered an explosion. The possibility of an explosion as a result of an autocatalytic criticality in the potential repository has been examined by the scientific community and found not to be credible (Canavan et al. 1995; Kastenberg et al. 1996).

4.3.3.2.2 Methodology for Criticality Evaluation

The complete evaluation process for postclosure criticality has been documented in *Disposal Criticality Analysis Methodology Topical Report* (YMP 1998), which has been reviewed by the NRC. Some aspects of the methodology have already been accepted by the NRC (Reamer 2000), which is providing additional information and refinement to allow for the acceptance of remaining aspects of the methodology (YMP 2000c).

The postclosure criticality methodology is based primarily on a risk-informed approach. The objective of the risk-informed methodology is to provide assurance that all known waste forms and associated degradation products that can result in configurations that can support criticality are considered and evaluated based on probability of occurrence and potential consequences. The bases of this risk-informed methodology are the estimated probabilities of the potential configurations that could lead to a criticality and the evaluation of the consequences of those criticalities. This methodology was designed to, and can, encompass time frames much greater than 10,000 years. This methodology requires a redesign of any proposed design concept that may result in a critical event that has a frequency of occurrence of greater than 1 in 10,000 per year for the entire repository in any of the first 10,000 years. The methodology also identifies potentially critical configurations that have such a low probability of occurrence that they are deemed not credible.

Figure 4-170 provides a visual representation of the postclosure criticality methodology. The starting point is the establishment of the range of:

1. Potential waste forms
2. Waste package and engineered barrier system designs
3. Characteristics of the site
4. Degradation characteristics of the waste package materials.

Some of these parameters can be specified deterministically, but some are most readily characterized probabilistically. Based on the established parameters, scenarios are developed encompassing how the emplaced material may degrade, which results in various degraded configurations. These configurations are grouped into classes reflecting a range of related parameters. Detailed degradation analyses are then performed on these configuration classes to identify the parameters that affect criticality potential: when the calculated k_{eff} of the configuration exceeds an established analytical value called the critical limit, the configuration is considered potentially critical (Section 3.5.2). These parameters include the respective quantities of fissile material, neutron absorber material, corrosion products, and moderator present in the configuration. Evaluations are then performed to determine the potential for criticality in the various proposed configuration classes (Section 3.5.2). Initially, the worst combination of parameters that define the range is used to determine whether that configuration class is potentially critical. If no combination of parameters can be

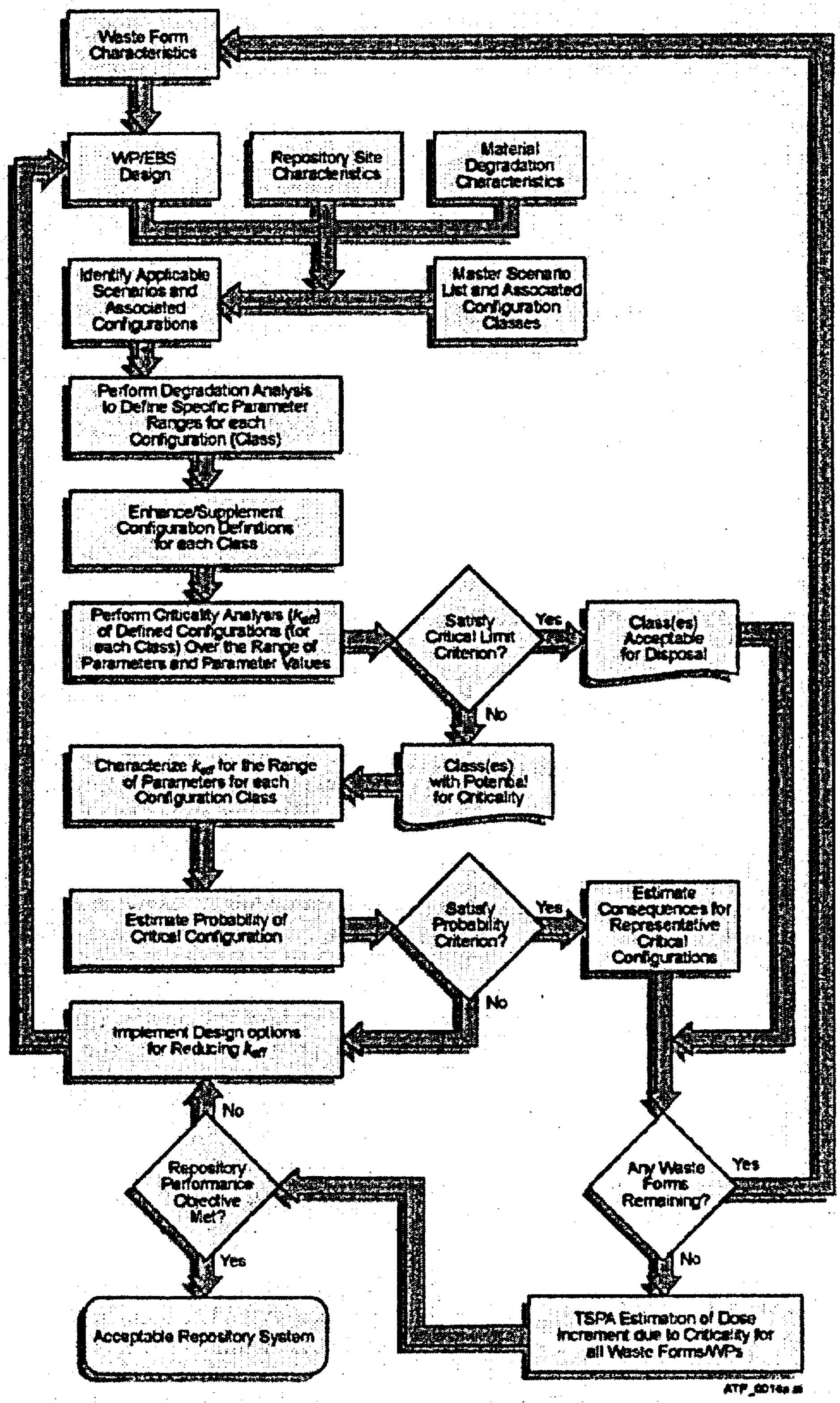

Figure 4-170. Representation of the Postclosure Criticality Methodology
WP = waste package; EBS = engineered barrier system. Source: YMP 2000c, Figure 3-1.

constructed such that probability of exceeding the critical limit is below the screening value, then that configuration class is considered acceptable for inclusion in the repository. Configuration classes that show a potential for criticality are evaluated further to more precisely define which parametric combinations result in a k_{eff} that exceeds the critical limit criterion.

The results of these k_{eff} calculations are tabulated to cover the range of parameter values. These tables are then used to determine whether a specific combination of parameters within a configuration class can be considered potentially critical.

The probability of exceeding the critical limit is estimated for each configuration class by comparing the characteristics of the waste stream to the established parameter ranges. A probability criterion is established to identify when the probability of criticality is considered so high that a redesign of the waste package or engineered barrier system is needed to reduce the probability of criticality. The probability criterion requires that the overall frequency of criticality be less than 1 in 10,000 per year for the entire repository in any of the first 10,000 years. The criticality limit and probability criterion form design criteria for limiting the potential for criticality in the repository during postclosure (CRWMS M&O 2000au; CRWMS M&O 2000bg).

If any configurations are determined to be capable of supporting criticality events and have an estimated probability of occurrence below the probability criterion, but contribute to a total probability of criticality for the entire repository inventory above the 10 CFR 63.114(d) (66 FR 55732) screening probability threshold of 10^{-4} in 10,000 years, consequence analyses are performed. The probability tested against this screening threshold is the sum of the probabilities for all the scenarios that can lead to criticality for all waste forms in the repository.

The consequence analyses are primarily concerned with the increase in the radionuclide inventory resulting from a criticality, but they include other potential consequences, such as increased waste package degradation due to the increased heat generated from the criticality.

In addition to the establishment of probability criteria, the overall risk of potential critical events is determined. The probabilities and associated consequences of all configurations that would contribute to the probability of exceeding the screening probability threshold (1 chance in 10,000 in 10,000 years) are collected into an input set to perform an additional TSPA. This TSPA, which includes the total criticality risk, is performed to determine if the health and safety of the public would be maintained within the proposed regulatory limit. If necessary, additional design features for reducing the potential level of criticality would be implemented.

As Figure 4-170 shows and the preceding paragraphs describe, the postclosure disposal analysis criticality methodology includes both deterministic and probabilistic aspects. The evaluation of the various long-term processes, the combination of events, any potential criticality, and the consequences resulting from a potential criticality are all deterministic analyses. However, probabilistic analyses are performed to establish the likelihood of a criticality occurrence.

The methodology as described in this section pertains to commercial and DOE spent nuclear fuel, DOE high-level radioactive waste, and immobilized plutonium. Criticality analyses for naval spent nuclear fuel employ a separate methodology that is primarily deterministic (YMP 1998, Section 1.2) and show that intact naval spent nuclear fuel cannot go critical for any credible configuration within the repository.

4.3.3.2.3 Criticality Results: Probability and Consequences

The methodology described in the previous section has been applied to postulated configurations that could result from the degradation of commercial spent nuclear fuel waste packages and their contents (CRWMS M&O 2000fh), as well as from several of the possible DOE spent nuclear fuel types (CRWMS M&O 1999j, 2000bh, 2000bi). The results, which demonstrate a very low probability of criticality and minimal consequences, are summarized below. These results apply to commercial spent nuclear fuel, except as otherwise noted. The 21-PWR waste package was chosen for these calculations because it is the design for fuel with the highest reactivity (CRWMS M&O 2000bg). Other waste forms with lower reactivity planned for repository disposal are expected to have a lower probability of criticality.

Probability of Criticality within 10,000 Years Following Repository Closure—The postulated earliest time to breaches in the waste package barrier that could allow criticality exceeds 10,000 years because of the limited water available in the natural system to contact the waste packages, the use of an extremely corrosion-resistant material for the waste package outer barrier, and a titanium drip shield that covers the tops of the waste packages and is designed to divert water away from the waste packages. Even with postulated early breaches, the initial conditions required for criticality would have a very low probability. The probability of a critical event, internal or external to the waste package, is expected to be less than 1 chance in 10,000 within 10,000 years (CRWMS M&O 2000fh, Section 6). The main possible exception to this pre-10,000-year conclusion is in the event of igneous intrusion. In that case, the combination of low probability for breach by igneous intrusion and the other conditions required for criticality (filling with water moderator and separating fissile material from neutron absorber) have been shown, for commercial spent nuclear fuel, to be well below the screening probability threshold (CRWMS M&O 2000fh, Section 6). Because of the combination of low probability for breach by igneous intrusion and other conditions required for criticality, other waste forms are expected to show similar results.

Probability of Internal Criticality—As mentioned previously, the probability of a waste package breach and subsequent loss of neutron absorber will increase with time after 10,000 years. Figure 4-171 depicts the different stages of internal degradation for a typical 21-PWR Absorber Plate waste package (YMP 1998, Appendix C). The final stages of degradation, shown in this figure, illustrate the collapse of the assemblies, which reduces the probability of criticality because of the reduced volume between fuel rods available for the moderator to fill. Another factor tending to reduce the probability of criticality with time is the eventual breach of the bottom of the waste package, which can drain most of the moderating water. Evaluations have shown that the potential for criticality of commercial spent nuclear fuel is maximized when the internal basket is fully degraded, but the assemblies remain intact (CRWMS M&O 1997d) and there is no breach of the bottom of the waste package. Using the TSPA-SR waste package degradation models, the probability of a critical event within the total inventory of the 21-PWR Absorber Plate waste packages is calculated to be 2×10^{-7} in 10,000 years (CRWMS M&O 2000fh, Section 6).

Probability of Internal Criticality for Codisposed U.S. Department of Energy Spent Nuclear Fuel and High-Level Radioactive Waste—Evaluations have been performed of the criticality potential of waste packages that would contain high-level radioactive waste glass and certain types of codisposed DOE spent nuclear fuel (CRWMS M&O 1996c, 1999j, 2000bh, 2000bi). These evaluations have generally shown the probability of criticality to be less than that for commercial spent nuclear fuel, which is very small to begin with. The primary reasons are the lower fissile loading per waste package for many of the DOE fuel types and the greater flexibility to install insoluble neutron absorber. This flexibility arises because of the smaller fuel mass per waste package.

Probability of Criticality for the Immobilized Plutonium Waste Form—The range of possible degradation scenarios for this waste form has been examined to identify potentially critical configurations. It was found that the design of the immobilized plutonium waste form itself provides several layers of defense in depth, so that criticality is virtually impossible (CRWMS M&O 2000ba). The degradation rate of the ceramic waste form is so slow that in the unlikely event that the waste package is breached and filled by a continuous dripping of water, it will be nearly 50,000 years after emplacement before enough of this waste form has degraded to permit any significant separa-

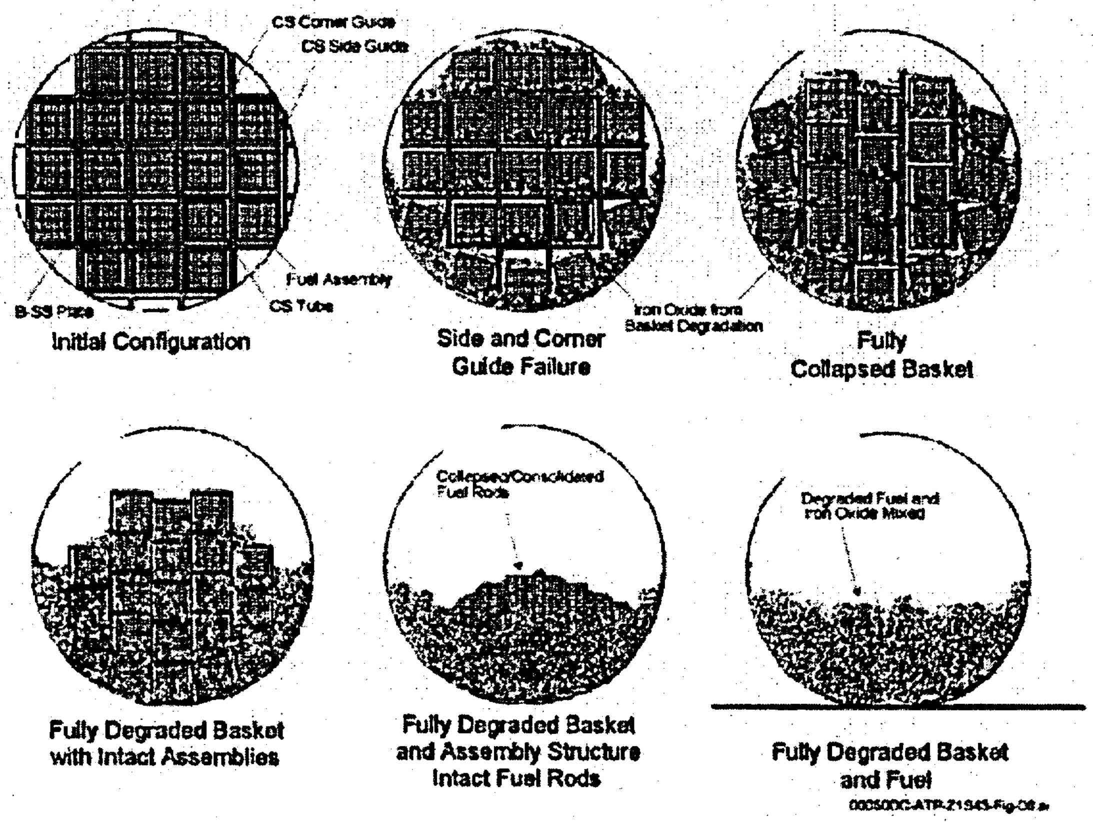

Figure 4-171. Different Stages of Internal Degradation for a Typical 21-PWR Absorber Plate Waste Package After 10,000 Years
CS = carbon steel; B-SS = borated stainless steel. Source: YMP 1998, Figure C-15.

tion of the uranium and plutonium from the gadolinium and hafnium neutron absorbers. Even after degradation of the waste form, the gadolinium and hafnium are generally less soluble than the fissile material, so they cannot be transported out of the waste package while the fissile material remains. Even with the additional conservative assumption of extremely unlikely chemistry conditions that would make the gadolinium sufficiently soluble to be removed before the fissile material, enough of the completely insoluble hafnium would remain to prevent criticality (CRWMS M&O 2000ba).

Probability of External Criticality—The probability for an external criticality to occur before 10,000 years is based on the igneous intrusion scenario. The probability for igneous intrusion is 1.6×10^{-4} in 10,000 years, which is just above the criticality-screening threshold of 1×10^{-4} in 10,000 years. However, subsequent processes to transport and accumulate the fissile material have a very small probability, so the combined probability of criticality before 10,000 years from igneous intrusion is less than the screening threshold (CRWMS M&O 2000fh, Section 6.2). Evaluations have shown that the probability, not considering igneous intrusion, of an external criticality even in the rock beneath the waste packages containing immobilized plutonium waste forms is less than 4×10^{-12} (McClure and Alsaed 2001, Section 8.4) and occurs beyond 10,000 years. This is primarily a result of (1) limited dripping water available to transport enough fissile mass out of the waste package and into a geometry favorable for criticality; (2) limited fracture intensity and lithophysae frequency to allow for fissile material accumulation in a geometry favorable for criticality; (3) low concentration of fissile material in the water trickling out of a breached waste package due to low waste form solubility; and (4) limited fresh water needed to dilute the effluent water and neutralize and precipitate the fissile minerals (McClure and Alsaed 2001, Section 8.4).

Steady-State Criticality Consequences—If a steady-state criticality were to occur, it would be very unlikely to have a power level greater than 5 kW because the power is limited by the evaporation of the water moderator, which increases with power level or temperature. The duration is likely to be limited to 10,000 years, which is the average period of a climate cycle that might have a high enough rainfall or drip rate to sustain the required level of water moderation against evaporation (YMP 1998, Appendix C, Section 5.1). For a typical commercial spent nuclear fuel waste package, a continuous steady-state criticality would result in an increase of the radionuclide inventory in that waste package by less than 30 percent at approximately 10,000 years (YMP 1998, Appendix C, Section 5.1). The return of a moist climate cycle, upwards of 10,000 years after the shutdown, would be very unlikely because continued degradation of the waste package would have removed some conditions necessary for criticality (e.g., intact waste package bottom that supports water ponding, or optimum spacing between fuel rods). When this moderate increase is spread over all the waste packages likely to be degraded and not critical, the increment in radionuclide inventory is likely to be much less than the 10 percent stated in the criticality consequence criterion in Section 4.3.3.2.2. The temperature increase during steady-state criticality will be too small to measurably enhance waste form or waste package degradation. Steady-state criticalities would not operate above boiling temperatures because such temperatures would boil away the water moderator and shut down the criticality (YMP 1998, Appendix C, Section 5.1), and no increased degradation rates have been observed in iron-based materials at 150°C (302°F) (CRWMS M&O 1996d, Volume III, p. 8-4). As a result, the incremental impact of steady-state criticality events on the total inventory for the repository is expected to be insignificant.

Transient Criticality Consequences—In the unlikely event that a transient criticality were to occur, a worst-case rapid initiating event would provide a uniform ramp of positive reactivity insertion lasting 90 seconds and producing a peak power level of 10 MW for less than 60 seconds (CRWMS M&O 1999q). This reactivity insertion profile reflects the most rapid redistribution of moderator from the initial configuration to one most favorable to criticality, most likely caused by a seismic disturbance. After this brief period, rapid boiling of the water moderator would shut down the criticality. Although 10 MW is 2,000 times larger than the power level of the steady state criticality, the short duration would limit the increase in radionuclide inventory. The inventory increment would be a factor of 100,000 smaller than that generated by the 10,000-year steady state criticality and a factor of 1 million smaller than that generated by the fuel during its use in a commercial reactor. Other consequences of a transient criticality would be a peak average fuel temperature of 233°C (451°F) and a peak overpressure of about 20 atmospheres (CRWMS M&O 1999q, Section 6.1). Both conditions would last 10 seconds or less and would not be expected to cause enough damage to the waste package or its environment to have a significant impact on repository performance.

Autocatalytic Criticality—This type of criticality has been found to be not credible for the potential repository (Paperiello 1995). Autocatalytic criticality is not possible at all for low-enriched waste forms, nor is it possible for the waste form inside the waste package. Even for highly enriched waste forms or those containing nearly pure plutonium-239, achieving a critical mass outside a waste package would require the entire fissile content of the waste package to be spread uniformly in a nearly spherical shape, or it would require the extremely unlikely commingling of large amounts of transported fissile material from at least two waste packages containing highly enriched waste forms (Canavan et al. 1995; CRWMS M&O 1996e). Because the igneous rock at Yucca Mountain is not likely to contain deposits that can efficiently accumulate fissile material, the probability of creating such a critical mass from a single or multiple waste packages containing highly enriched waste forms is so low as to be not credible (Kastenberg et al. 1996).

Disruptive Natural Events—The potential impact of disruptive natural events (e.g., seismic or igneous intrusion) on the risk of criticality in the repository has also been studied. Seismic events can produce a rapid change in the configurations of waste forms and waste packages. If the resulting configuration has a k_{eff} above the critical limit, the seismic event has provided a rapid reactivity insertion mechanism that could lead to a transient criticality. The identification of the initial, preinsertion configurations has been incorporated into the repository criticality analysis methodology.

Igneous intrusion was considered because its expected probability, 1.6×10^{-4} in 10,000 years, is above the screening threshold. The potential adverse criticality impacts of igneous intrusion into the repository include (1) the possibility of immediate waste package breach; (2) the separation of a significant fraction of the fissile material from the neutron absorber by magma transport; and (3) the accumulation of a critical mass of fissile material from, or within, the transporting magma. The potential for criticality following igneous intrusion has been evaluated for commercial spent nuclear fuel, under extremely conservative assumptions, and no mechanism for accumulating a critical mass has been identified (CRWMS M&O 2000fh). It is expected that a similar analysis for higher enriched spent nuclear fuel would give similar results. In particular, it is expected that although the probability of igneous intrusion is slightly greater than the screening probability threshold, when the low probability of the other conditions required for criticality is included, the combined probability of criticality will be below the screening probability threshold (CRWMS M&O 2000fh).

4.3.3.2.4 Conclusions

To ensure thorough consideration of all possibilities for criticality, a risk-informed methodology for postclosure criticality has been developed, as described in *Disposal Criticality Analysis Methodology Topical Report* (YMP 1998; YMP 2000c). The methodology encompasses time frames well beyond 10,000 years. It identifies configurations that can become critical and estimates the probability of occurrence and the consequences of those criticalities. The methodology also includes threshold criteria that identify potentially critical configurations having too high a probability of occurrence. The purpose of these criteria is to identify any need for criticality design enhancement. These criteria are applied before any inclusion of potential criticalities into TSPA analyses. Additional TSPA analyses will be performed, including criticality results, if the combined probability of all the criticality events is above the screening probability threshold (1 chance in 10,000 in 10,000 years) or if a particular criticality event would significantly affect repository performance.

Evaluations have thus far shown that the probability of postulated criticality events before 10,000 years is below the threshold for inclusion in the nominal case for *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a, Section 4.5.6). Accordingly, criticality is not included in the TSPA-SR nominal case. While the criticality methodology has not been fully applied to evaluation of all the waste forms expected to be placed in the potential repository, many have been evaluated, and the rest are expected to yield similar results. Therefore, the calculations performed to date indicate that the expected total probability of criticality will remain below the threshold for inclusion in the TSPA nominal case before 10,000 years.

In the unlikely event that a criticality occurs, it would most likely be steady-state, and the primary consequence would be an increase in the radionuclide inventory. The principal consequences of a transient criticality would be increased temperature and pressure. These have been evaluated and found to be of such short duration that they would be insignificant to repository performance. Potential autocatalytic criticalities have been evaluated and are not credible events.

4.4 ASSESSMENT OF PERFORMANCE

A major component of the postclosure repository safety case is the quantitative analysis of repository performance presented in this section. The DOE has conducted a TSPA to evaluate the performance of a potential geologic repository at Yucca Mountain.

The TSPA was divided into separate evaluations: (1) a nominal (or reference) scenario and (2) a disruptive scenario. For groundwater protection, "undisturbed performance" was analyzed, consistent with 10 CFR 63.331 (66 FR 55732), and considered in this report equivalent to the nominal scenario. For individual protection, overall system performance was analyzed, consistent with 10 CFR Part 63. Therefore, the individual protection analyses combined the TSPA results for both the nominal and disruptive scenarios but excluded the human intrusion scenario, consistent with 10 CFR 63.113(d).

Presentations of TSPA-SR model results and supporting analyses for the evaluation of individual protection and groundwater protection are found in Section 4.4.2 and in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a, Sections 4.1 and 4.2). These analyses were consistent with proposed EPA (64 FR 46976) and NRC (64 FR 8640) rules.

Additional information on the supplemental TSPA model results is found in Volume 2 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b), Sections 3.2, 4, 4.1, and 4.2 (for the nominal scenario) and Section 3.3 (for the disruptive scenario). These results were also based on proposed EPA and NRC rules, but the report did provide a qualitative assessment of results consistent with the final EPA standard at 40 CFR Part 197.

Revised supplemental TSPA model results consistent with the final EPA rule can be found in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Section 6). Results of TSPA sensitivity analyses consistent with the final NRC rule at 10 CFR Part 63 (66 FR 55732), using the revised supplemental TSPA model, are presented in *Total System Performance Assessment Sensitivity Analyses for Final Nuclear Regulatory Commission Regulations* (Williams 2001b).

The DOE evaluated the performance of the system where there is a human intrusion, consistent with NRC regulations. The evaluation method in both cases is the same, except that the TSPA method for human intrusion used assumptions about the human intrusion scenario consistent with 10 CFR Part 63 (66 FR 55732). The DOE determined that, after about 30,000 years, the waste packages could degrade sufficiently that a human intrusion could occur without recognition by the driller. A human intrusion at that time was analyzed, and the results of the analysis are presented in the Yucca Mountain EIS and Section 4.4 of this report. Summary results of the earlier TSPA-SR model evaluation of inadvertent human intrusion at 100 years, consistent with proposed NRC (64 FR 8640) and EPA (64 FR 46976) rules, were discussed in *Yucca Mountain Preliminary Site Suitability Evaluation* (DOE 2001b) and are presented in Section 4.4.4 of this report. Results of the supplemental and revised supplemental TSPA models are discussed in Volume 2, Section 4.1.3 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b), in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a), and in Section 4.4.4 of this report.

A human intrusion preceded by an unlikely igneous intrusion is analyzed in *Total System Performance Assessment Sensitivity Analyses for Final Nuclear Regulatory Commission Regulations* (Williams 2001b, Section 6.2).

This section focuses on explaining the primary results and technical findings of the TSPA calculations. For the purposes of this discussion, the analyses are presented in three scenarios: nominal (i.e., reference), disruptive (i.e., igneous activity), and human intrusion (i.e., penetration of the repository as a result of exploratory drilling for groundwater).

The analysis of FEPs conducted to determine their importance to the performance of the repository system led to the exclusion of some FEPs because of low probability or low consequence. For example, the criticality and large seismic event FEPs were excluded from the nominal and disruptive analyses based on these criteria.

The TSPA results quantify the performance of the potential repository for 10,000 years. To complement the results of the 10,000-year performance assessment, the peak dose to the reasonably maximally exposed individual beyond the 10,000-year time period has been calculated. TSPA results for 100,000 and 1 million years were calculated for the nominal case to gain insight into possible peak dose levels at times significantly beyond 10,000 years.

Section 4.4.1 describes the TSPA model in general, together with a discussion of how uncertainty is identified and incorporated in the model. It also describes the disruptive scenarios analyzed and summarizes the radionuclides considered in the dose assessment. The sections that follow present the primary TSPA results for:

1. Evaluation of system and barrier component performance for the nominal scenario (Section 4.4.2)

2. Evaluation of the effect on repository performance of direct and indirect releases for the disruptive scenario associated with igneous activity (Section 4.4.3)

3. Evaluation of the impact on repository performance associated with inadvertent human intrusion by drilling through the repository (Section 4.4.4)

4. Sensitivity and uncertainty analyses for the nominal, disruptive, and human intrusion scenarios (Section 4.4.5).

Summary of Results—Table 4-33 presents a summary of recent TSPA results for: (1) individual protection, (2) human intrusion, and (3) groundwater protection. The combined dose calculated from the nominal and disruptive events scenarios for individual protection is 0.1 mrem/yr. The TSPA-SR model calculated a combined dose of 0.08 mrem/yr, whereas the revised supplemental TSPA analyses yielded a calculated dose of 0.1 mrem/yr. TSPA results for each scenario (nominal, disruptive, and human intrusion) are presented below.

Nominal Scenario—The DOE has assessed the repository's performance for the nominal case. The TSPA-SR model projected no dose over a 10,000-year period. The supplemental TSPA model projected a dose to the reasonably maximally exposed individual of 2×10^{-4} mrem/yr, while the revised supplemental TSPA model projected a dose of 1.7×10^{-5} mrem/yr over a 10,000-year period. The doses calculated by the supplemental and revised supplemental TSPA models would be reduced by approximately one-third if an annual water demand of 3,000 acre-ft consistent with NRC regulations was used (see 10 CFR 63.312) (Williams 2001b, Section 6.3).

Disruptive Scenario—The primary disruptive event considered in these analyses is igneous activity. The TSPA models evaluated two igneous disruptions: a volcanic eruption that intersects drifts and brings waste to the surface; and an igneous disruption that damages waste packages and exposes radionuclides for groundwater transport. The probability of igneous disruption is extremely low (the mean annual probability is about one chance in 70 million per year of occurring). The TSPA-SR model projected a dose from igneous activity of 0.08 mrem/yr over a 10,000-year period, and both the supplemental TSPA model and the revised supplemental TSPA model projected a dose to the receptor of 0.1 mrem/yr over 10,000 years.

Human Intrusion Scenario—The DOE has assessed the consequences of a stylized human intrusion into the repository at 100 years after closure, pursuant to the proposed NRC regulation. The results of this analysis show that the peak mean dose is approximately 0.01 mrem/yr over a 10,000-year period. Consistent with final NRC regulations at 10 CFR 63.321, the DOE analyzed the period of time that would be necessary for waste packages to degrade sufficiently that a human intrusion could occur without recognition by a driller. The DOE subsequently found that

Table 4-33. Summary Postclosure Dose and Activity Concentration Limits and Evaluation Results

		Results from TSPA-SR Model[a]	Results from Supplemental TSPA Model[b]	Results from Revised Supplemental TSPA Model[c]	Summary of Results
Individual protection		0.8 mrem/yr[d]	0.1 mrem/yr[d] (HTOM) 0.1 mrem/yr[d] (LTOM)	0.1 mrem/yr[d] (HTOM) 0.1 mrem/yr[d] (LTOM)	0.1 mrem/yr[d] (HTOM) 0.1 mrem/yr[d] (LTOM)
Human intrusion		≤0.01 mrem/yr[e]	0.0 mrem/yr[f]	0.0048 mrem/yr[e] 0.0 mrem/yr[f]	0.0 mrem/yr[f]
Groundwater protection	Combined radium-226 and radium 228, including natural background	≤1.04 pCi/L[g]	≤1.04 pCi/L[g] (HTOM) ≤1.04 pCi/L[g] (LTOM)	≤1.04 pCi/L[g] (HTOM) ≤1.04 pCi/L[g] (LTOM)	≤1.04 pCi/L[g] (HTOM) ≤1.04 pCi/L[g] (LTOM)
	Gross alpha activity (including radium-226 but excluding radon and uranium), including natural background	≤1.1 pCi/L[g,h]	≤1.1 pCi/L[g,h] (HTOM) ≤1.1 pCi/L[g,h] (LTOM)	≤1.1 pCi/L[g,h] (HTOM) ≤1.1 pCi/L[g,h] (LTOM)	≤1.1 pCi/L[g,h] (HTOM) ≤1.1 pCi/L[g,h] (LTOM)
	Dose to the whole body or any organ from combined beta- and photon-emitting radionuclides	0.0 mrem/yr[i]	5×10^{-5} mrem/yr (HTOM) 2×10^{-5} mrem/yr (LTOM)	2.2×10^{-5} mrem/yr (HTOM) 1.5×10^{-5} mrem/yr (LTOM)	2.2×10^{-5} mrem/yr (HTOM) 1.5×10^{-5} mrem/yr (LTOM)

NOTES: [a]Source: CRWMS M&O 2000a, Sections 4.1.5, 4.2.2, and 4.4.2.
[b]Source: BSC 2001a, Appendix A; BSC 2001b, Sections 5.1, 5.2, and 5.5.
[c]Source: Williams 2001a, Sections 6.2, 6.4, and 6.6.
[d]Probability-weighted peak mean dose equivalent for the nominal and disruptive scenarios, which include igneous activity; results are based on an average annual water demand of approximately 2,000 acre-ft; the mean dose for groundwater-pathway-dominated scenarios would be reduced by approximately one-third by using 3,000 acre-ft.
[e]Peak mean annual dose for a human intrusion at 100 years.
[f]Human-intrusion-related releases are not expected during the period of 10,000 years after disposal; the DOE has determined that the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the driller is at least 30,000 years.
[g]These values represent measured natural background radiation concentrations; calculated activity concentrations from repository releases are well below minimum detection level and background radiation concentrations.
[h]Gross alpha background concentrations are 0.4 pCi/L ±0.7 (for maximum of 1.1 pCi/L).
[i]Nominal scenario showed no releases from waste packages before 10,000 years.
HTOM = higher-temperature operating mode; LTOM = lower-temperature operating mode.

human intrusion would not occur for more than about 30,000 years. Therefore, no doses related to human intrusion would occur within 10,000 years. The dose from a human intrusion at 30,000 years is analyzed and presented in the final EIS.

4.4.1 Total System Model

The Yucca Mountain repository system is a combination of integrated processes. The system can be conceptualized and modeled as a collection of component models that are coupled. The basic objective of the waste disposal system is to contain and isolate the radioactive wastes so that the dose impact to humans does not exceed levels considered potentially harmful to human health and the environment, as specified by applicable radiation protection standards. Analysis of the system requires development of conceptual and numerical models for each of the major components.

Figure 4-172 illustrates the process for constructing a TSPA model using the performance assessment pyramid. It shows how more detailed underlying information builds the technical basis for the total system models. The breadth of the pyramid's lowest level represents the complete suite of process and design data and information, along with the field and laboratory studies that are the first step in understanding the system. The next higher level indicates how the data feed into

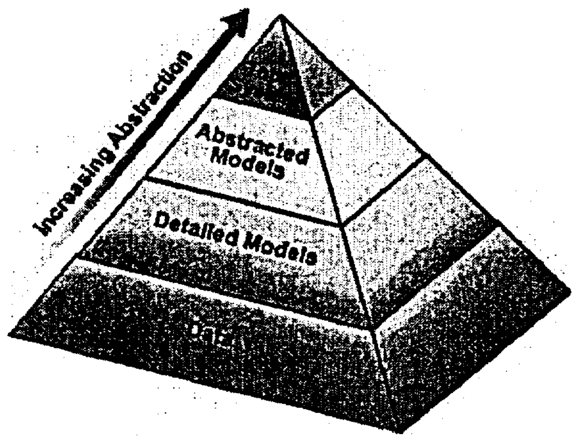

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Figure 4-172. Relationship of Data, Models, and Information Flow in the Total System Performance Assessment Model

conceptual models that visualize the operation of the individual system components.

The next higher level represents the synthesis of information from lower levels of the pyramid into computer models. At this point, the subsystem behavior may be described by linking models together into representations; this is where performance assessment modeling is usually thought to begin. The term "abstraction" is used to indicate the extraction of essential information. TSPA models are usually referred to as abstracted models.

The upper level shows the final level of distillation of information into only the most critical aspects to represent the total system. At this point, all the models are linked together. These are the models used to forecast system behavior and estimate the likelihood that the behavior will comply with proposed regulations and ensure long-term safety.

As information is transferred up the pyramid, it generally is distilled into progressively more simplified forms, or becomes more abstracted, as Figure 4-172 indicates. However, abstraction is not necessarily synonymous with simplification. If a particular component model cannot be simplified without losing essential aspects, it ceases to move up the pyramid and becomes part of the TSPA calculation tool. Therefore, an abstracted model in a TSPA may take the form of something as simple as a table of values calculated using a complex computer model or as complex as a fully three-dimensional computer simulation. However, even the most complex models of specific processes are still abstractions of reality.

Several considerations dictate the level of complexity used to represent a process. One is the sensitivity of the results of the TSPA to that particular process. The more sensitive the process or parameter, the more detailed the model representation tends to be. However, the degree of complexity is also limited by the state of knowledge concerning the model.

Figure 4-173 shows, and Table 4-34 lists, the major components in the TSPA model. Starting in the upper left part of the wheel for the nominal scenario, the components are unsaturated zone flow, engineered barrier system environment, waste package and drip shield degradation, waste form degradation, engineered barrier system transport, unsaturated zone transport, saturated zone flow and transport, and biosphere. The volcanic scenario affects these components but does not increase their number. The human intrusion scenario is a stylized calculation (consistent with EPA and NRC regulations); it requires alteration of the engineered barrier system components, but does not require additional components.

TSPAs are based on a number of building blocks. Principal among these are models that describe what happens to Yucca Mountain in the presence of a repository and how the engineered system behaves within the environmental setting of the mountain. Each model is designed to describe the behavior of individual and coupled physical and chemical processes. A significant portion of the DOE site characterization program has been aimed at developing the scientific basis for the most reasonable representation of the Yucca Mountain site and its associated engineered barriers. This scientific basis serves as the foundation for the process models used in the development of the TSPA. Section 4.2 describes the basis for these models in more detail.

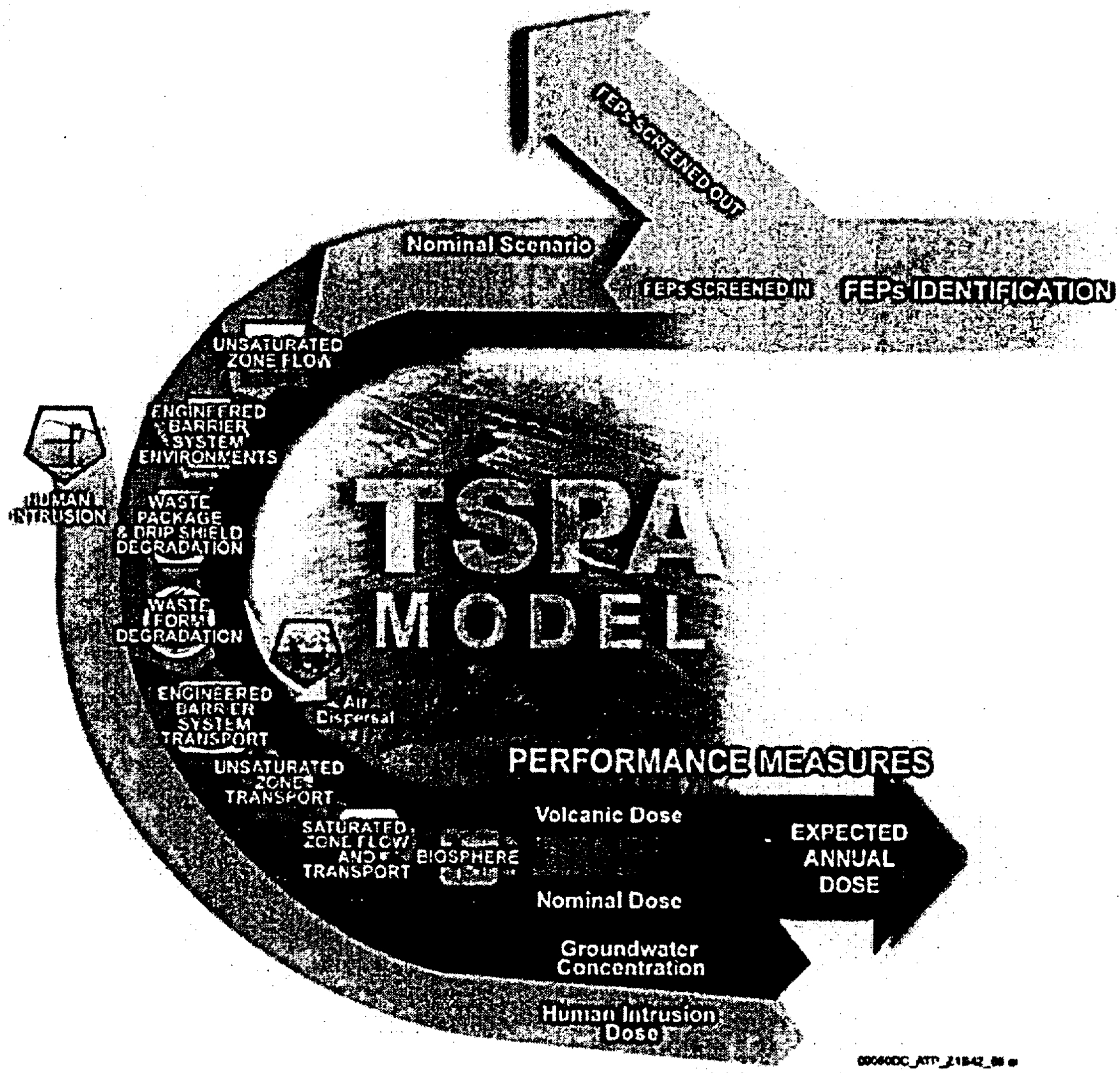


Figure 4-173. Schematic of the Principal Process Models Included in the Nominal and Disruptive Event Scenarios

Table 4-34. Total System Performance Assessment Model Components

TSPA Model Components	Subsystem Model
Unsaturated zone flow	Climate, infiltration, unsaturated zone flow above repository, seepage, coupled processes effects on unsaturated zone flow
Engineered barrier system environment	Mountain scale thermal-hydrologic model, drift scale thermal-hydrologic model, in-drift geochemical model
Waste package and drip shield degradation	Waste package and drip shield degradation model
Waste form degradation	Solubilities, inventory, in-package chemistry, colloid model, cladding degradation model, waste form dissolution model, seismic cladding model
Engineered barrier system transport	Radionuclide transport model, colloid model
Unsaturated zone transport	Unsaturated zone transport model, colloid model
Saturated zone flow and transport	Saturated zone flow and transport model
Biosphere	Soil removal, biosphere dose conversion factor, well head dilution
Volcanism	Direct release model, indirect release model

4.4.1.1 Components and Integration of the Total System Performance Assessment Model

The Yucca Mountain repository system consists of the geologic setting and engineered barriers, which together are aimed at reducing the exposure of humans to radioactive materials to acceptable levels. This section briefly describes the key aspects of the individual component models identified in Table 4-34 and Figure 4-173. Section 4.2 presented more detailed discussion of the processes that may affect repository performance.

Several components—climate, infiltration, and unsaturated zone flow—define the temporal and spatial distribution of water flow through the unsaturated tuffs above the water table at Yucca Mountain and the temporal and spatial distribution of water seeps into the repository drifts. As described in Section 4.2.1, long-term climate variations are expected to occur. In addition, the thermal conditions generated by the decay of the radioactive wastes can mobilize water until the heat of the waste has decreased. The movement of water around drifts varies as a function of temperature (BSC 2001a, Section 11.2.5; BSC 2001b, Section 3.2.2.1). For these reasons, the amount of water flowing in the rock and seeping into drifts is expected to vary with time.

Additional components (drift-scale thermal hydrology, in-drift geochemical environment, and drip shield and waste package degradation) define the spatial and temporal distribution of the calculated breach of the waste packages. The most important environmental factors affecting waste package containment time are the thermal, hydrologic, and geochemical processes acting on the surface of a waste package. The degradation characteristics of the waste package materials (e.g., susceptibility to corrosion) also impact the timing of waste package breaches. Mechanical degradation processes (e.g., from rockfall) are insignificant in affecting containment time.

The environmental processes acting on the surface of a waste package, as well as the timing and extent of waste package degradation, relate directly to the selected design. It is appropriate to review the key aspects of the design described in Section 2 as they relate to the expected behavior of the repository system. Most relevant to performance is the waste package reference design, which consists of a dual barrier of metal: an outer metal barrier of Alloy 22 and an inner metal barrier of Stainless Steel Type 316NG. The principal waste forms to be disposed of within these waste packages are:

- Commercial spent nuclear fuel from pressurized water reactors or boiling water reactors
- DOE spent nuclear fuel, including N Reactor fuel from Hanford, research reactor fuel, and naval spent nuclear fuel
- High-level radioactive waste, in the form of glass logs in stainless steel canisters from Savannah River, South Carolina; Hanford, Washington; and Idaho National Engineering and Environmental Laboratory, Idaho
- DOE stabilized excess weapons-grade plutonium in a ceramic matrix placed in canisters of vitrified DOE high-level radioactive waste.

The waste packages are designed to contain up to 21 pressurized water reactor assemblies, 44 boiling water reactor assemblies, 5 glass logs codisposed with DOE spent nuclear fuel assemblies, or other canistered DOE spent nuclear fuel, including naval spent nuclear fuel.

The engineered barrier system contains a drip shield system over the waste packages, intended to shield the waste packages from dripping water and rockfall. The drip shield consists of a 15-mm (0.6-in.) thick titanium alloy.

Key aspects of the design that influence the long-term performance of the disposal system include:

- Areal thermal loading, which is a function of the contents of waste packages and the spacing between waste packages and between emplacement drifts
- Size of the drifts

- Characteristics of the engineered materials placed in the drifts to support the waste package (the waste package supports and inverts).

These aspects of the design affect (1) the thermal load of the repository, which affects the distribution of water in and around the waste packages; (2) the degradation of the waste packages; and (3) the release pathways and characteristics from the waste packages through the invert.

The analysis of the performance of the disposal system involves an evaluation of the release of radionuclides from breached waste packages. The design is used as a basis for the analysis, then other key processes are imposed on the design, including seepage into the waste package, cladding degradation, colloid formation and stability, waste form degradation, and transport within the waste package. The degradation of the waste form components leads to a determination of the spatial and temporal distribution of the mass of radioactive wastes released from the waste packages. Waste package degradation and radionuclide release depends on the thermal, hydrologic, and geochemical conditions inside the waste package, which change with time.

Evaluation of the concentration of radionuclides in groundwater includes an evaluation of the evolution of the designed system, as well as radionuclide transport through the engineered barrier system, the unsaturated zone, and the saturated zone and radionuclide transport in the biosphere. These components of the total system cause the spatial and temporal variation of radionuclide concentrations in groundwater. The groundwater concentration ultimately yields the mass of radionuclides that may be ingested or inhaled by individuals exposed to that groundwater, which in turn causes a level of radiological dose or risk associated with that potential exposure. Radionuclides may be transported either by advection (radionuclide movement that occurs with the bulk movement of the groundwater), diffusion (radionuclide movement that occurs because of a concentration gradient), or colloid-facilitated transport. The concentration depends on both the mass release rate of the radionuclides and the volumetric flow of water along the different pathways in the different components.

Each of these aspects of the TSPA model is used in describing the behavior of the Yucca Mountain repository system. They describe the FEPs that are expected to occur in the potential repository throughout the period of interest. Igneous activity, with its low probability of occurrence, is considered separately in the disruptive events scenario in TSPA analyses. In addition, a human intrusion scenario is considered by a separate TSPA.

4.4.1.2 Treatment of Uncertainty in Total System Performance Assessment Analyses

Because uncertainty is unavoidable in long-term assessments of repository performance, both EPA and NRC regulations describe a TSPA methodology that is designed to explicitly incorporate uncertainty in the analyses. Therefore, the DOE has developed a TSPA method that applies a probabilistic framework in which uncertainties associated with scenarios, models, and parameters are explicitly incorporated into the performance assessments.

The result of a TSPA is a quantitative estimate of the expected annual dose, weighted by probability of occurrence, to an individual whose characteristics are consistent with definitions in the regulations. The performance assessment analyzes what can happen at the repository after permanent closure, how likely it is to happen, and what can result, in terms of dose. Taking into account, as appropriate, the uncertainties associated with data, methods, and assumptions used to quantify repository performance, the performance assessment is expected to provide a quantitative evaluation of the overall system's ability to achieve the performance objective.

Consistent with EPA and NRC regulations, the expected annual dose calculated by the TSPA is the expected value of the annual dose considering the probability of the occurrence of the events and the uncertainty, or variability, in parameter values used to describe the behavior of the geologic repository. The expected annual dose is calculated by accumulating the dose estimates for each year, where the dose estimates are weighted by the probability of the events and the parameters leading to the dose estimate. All of the TSPA models described in this report have been developed consistent with EPA and NRC regulations.

Assessment of the long-term performance of a potential repository at Yucca Mountain involves complex modeling of various coupled hydrologic, geochemical, thermal, and mechanical processes taking place within the engineered and natural barriers over an extended period of time. The future evolution of the geologic and environmental conditions surrounding the repository is also considered.

This section discusses the nature and sources of the uncertainties involved in assessing performance, describes the probabilistic framework to be used in the TSPA calculations, and presents the steps required for the propagation of uncertainty in the TSPA model.

Nature and Sources of Uncertainty—Uncertainty will exist in any projection of the geologic and environmental conditions surrounding the potential repository 10,000 years into the future.

Scenario uncertainty refers to uncertainty about future states of the repository system. Plausible future states of the repository system, as well as their likelihood of occurrence, must be inferred from direct and indirect field evidence and incorporated into performance assessment analyses. Examples of uncertain scenarios include volcanic activity, resulting in upward magma flow to the repository horizon and damage to the waste containers, or a change in climate from present-day conditions to a wetter climate.

Model uncertainty can be separated into mathematical model uncertainty and conceptual model uncertainty. Mathematical model uncertainty arises from the simplifying assumptions and approximations made in formulating the mathematical equations used in the TSPA component models. Consequently, component models of the individual natural or engineered barriers are limited in their capability to simulate accurately the behavior of real processes (see Section 4.2). Conceptual model uncertainty refers to an incomplete understanding of what processes dominate system behavior or how different processes might affect one another; therefore, conceptual model uncertainty reflects a state of imperfect or incomplete knowledge. Mathematical model uncertainty can be characterized by comparing computer model calculations with field and laboratory experiments which constitutes a form of model validation. In contrast, conceptual model uncertainty is addressed by evaluating plausible alternative conceptual models of process relationships. The parameters of the model used to predict the performance of the repository system are subject to uncertainty and variability. Uncertainty in model parameters arises from incomplete field-scale knowledge or limited data. Uncertainty can be reduced with additional measurements; an example is the additional data being gathered on the solubility of neptunium in groundwater, which is not known with certainty.

Variability arises from the randomness or heterogeneity of physical or behavioral characteristics. Since variability is an intrinsic property of a system, it can be quantified, but it cannot be reduced with additional information; an example is the infiltration flux into the unsaturated zone at the surface of Yucca Mountain.

Variability and uncertainty are often combined in a single parameter because the information that scientists can obtain is imprecise; an example would be the seepage flux contacting waste packages. This flux varies from location to location within the repository horizon because of underlying heterogeneities in hydrogeologic properties. In addition, the value of flux at any given location is uncertain because of limited characterization of the natural system.

Since many of the TSPA model inputs (i.e., scenarios, mathematical/conceptual models, and parameters) are uncertain or variable, the output of the model will also reflect that uncertainty. A probabilistic framework has been adopted in the TSPA-SR model and supplemental TSPA models for addressing variability and uncertainty in a manner that is consistent with the regulatory standards promulgated by the EPA and NRC.

Probabilistic Framework for Implementing Performance Assessment—The DOE has performed a quantitative evaluation of the potential performance of a repository at Yucca Mountain using probabilistic methods so as to explicitly incorporate the various possible states and their relative likelihoods. The probabilistic framework used in TSPA calculations is a relatively well-established methodology for incorporating the effects of uncertainties in scenarios, conceptual models, and parameters. It has been used extensively in probabilistic risk analyses for evaluating the safety of nuclear reactors and power plants (Rechard 1999). Several probabilistic performance assessments have also been carried out in the national radioactive waste disposal program. These include a series of studies for the disposal of transuranic waste at the Waste Isolation Pilot Plant in New Mexico (Helton, Bean et al. 1998), as well as a series of calculations performed for the disposal of high-level radioactive waste at Yucca Mountain by the DOE (Barnard et al. 1992; Wilson, M.L. et al. 1994; CRWMS M&O 1994, 1996f, 1998g) and the NRC (Codell et al. 1992; Wescott et al. 1995).

Monte Carlo simulation, the most commonly employed technique for implementing the probabilistic framework in engineering and scientific analyses, is a numerical method for solving problems by random sampling (Cullen and Frey 1999). As shown in Figure 4-174, this method allows a full mapping of the uncertainty in model parameters (inputs) and future system states (scenarios), expressed as probability distributions, into the corresponding uncertainty in model predictions (output). Output is also expressed in terms of a probability distribution. Uncertainty in the model outcome is quantified through multiple model calculations, using parameter values and future states drawn randomly from prescribed probability distributions. The Monte Carlo simulation technique is also called the method of statistical trials

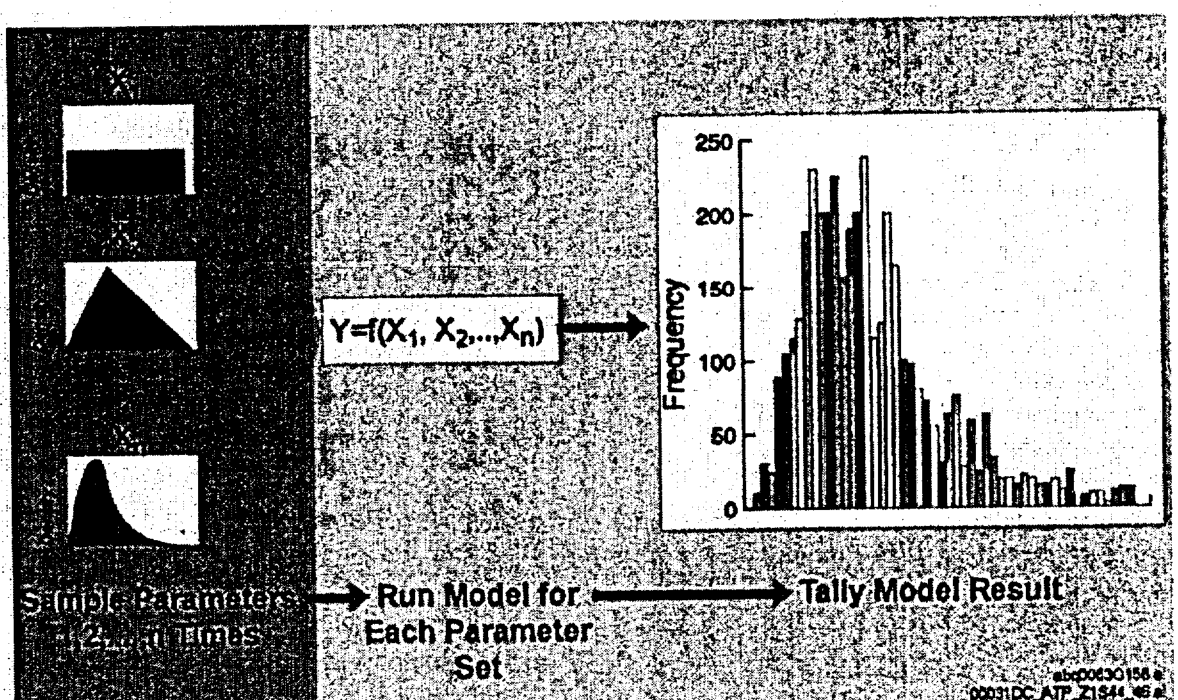


Figure 4-174. Monte Carlo Simulation
The most commonly employed technique for implementing the probabilistic framework in engineering and scientific analyses is a numerical method for solving problems by random sampling (Morgan et al. 1990). This method allows a full mapping of the uncertainty in model parameters (inputs) and future system states (scenarios), expressed as probability distributions, into the corresponding uncertainty in model predictions (output).

because it uses multiple realizations of the inputs to compute a probabilistic outcome.

The probabilistic modeling approach is computationally demanding. It requires several hundred model calculations for each scenario of interest. However, it provides important information not available from a deterministic "best-guess" or "worst-case" calculation. The benefits of probabilistic modeling include (1) obtaining a reasonable approximation of the full range of possible outcomes (and the likelihood of each outcome) to quantify predictive uncertainty and (2) analyzing the relationship between the uncertain inputs and the uncertain outputs to provide insight into the most important parameters.

Quantified Uncertainties in the TSPA Model—To describe system properties realistically, input parameters used in the TSPA component models must reflect the associated degree of uncertainty and variability in the numerical values. Uncertainty in input values can arise because of (1) limited data, (2) measurement resolution, (3) estimation error, and (4) scaling approximations. In contrast, variability in model parameters can be the direct result of the heterogeneous nature of the process, as in the case of geologic materials. Laboratory data for physical properties of geologic media, such as porosity and permeability, exhibit a scattering of values, which is the effect of spatial variability. In a number of cases, input parameters exhibiting spatial variability follow well-known statistical distributions. In addition, input parameters can exhibit variability in time, as in the cases of precipitation, wind speed, wind direction, and other meteorologic parameters.

Input uncertainty and variability are explicitly represented in the TSPA by assigning empirical probability distributions, derived in one of the following ways:

1. Fitting of laboratory or field data with standard statistical distributions
2. Abstracting (i.e., distilling and simplifying) the quantitative results from process model simulations
3. Selecting bounding distributions (i.e., covering the range of variability of data) based on scientific inferences from theoretical calculations or indirect evidence
4. Translating expert judgment into statistical distributions through a formal elicitation procedure.

These probability distributions are then sampled in the Monte Carlo simulation (Cullen and Frey 1999, Chapter 7) to propagate their effects on the TSPA projections for annual dose.

The DOE quantified many uncertainties in Volume 2, Section 3 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b). These analyses were based on reevaluating uncertainty in several component models:

1. Seepage into drift(s)
2. Coupled effects on seepage
3. Water diversion performance of engineered barrier systems
4. In-drift moisture distribution
5. Drip shield degradation and performance
6. In-package environments
7. Cladding degradation and performance
8. DOE high-level radioactive waste degradation and performance
9. Dissolved radionuclide concentrations
10. Colloid-associated radionuclide concentrations
11. Invert degradation and transport.

These component models are also discussed in Sections 4.2 and 4.4.5.5 of this report.

Propagation of Parameter Uncertainty—The propagation of parameter uncertainty involves performing a Monte Carlo analysis with the TSPA model, a four-step process that is described below.

In the TSPA methodology, the Monte Carlo approach is applied to each scenario separately, and then the results are combined based on the probability of each scenario. All the TSPA models use the same basic methodology.

1. **Identifying imprecisely known model input parameters to be sampled**—The TSPA-SR model and supplemental and revised supplemental TSPA models consist of approximately 1,000 parameters, many of which are uncertain or variable. Scientists determine which of these have a significant range of uncertainty or variability and, therefore, should be statistically sampled during model calculations and during the development of individual process models or abstractions. Section 3 of *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a) provides more explanation on the selection of these parameters for the TSPA-SR model. The *FY01 Supplemental Science and Performance Analyses* (BSC 2001a; BSC 2001b) and *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a) present more information on the parameters used in the supplemental and revised supplemental TSPA models.

2. **Constructing probability distribution functions for each of these parameters**—The probabilistic framework employed in the Monte Carlo simulations requires that the uncertainty in model inputs be quantified using probability distributions. The construction of probability distributions has focused on the full range of defensible and reasonable parameter distributions that can be justified on the basis of available information or expert elicitation. These distributions are specified either as empirical distribution functions (i.e., individual values and their likelihood) or as the coefficients of parametric distributions fit to data (e.g., the mean and standard deviations of a normal distribution fit to porosity data).

3. **Generating a sample set by selecting a parameter value from each distribution**—The next step in the Monte Carlo process requires generating a number of equally likely input data sets. These consist of parameter values randomly sampled from the prescribed range and distributions. An improved form of random sampling is the Latin Hypercube sampling procedure, where the range of each parameter is divided into several intervals of equal probability and a value is selected at random from each interval (Helton, Bean et al. 1998). This method, which was employed in the TSPA-SR, the supplemental and revised supplemental TSPA models, helps achieve a statistically more uniform coverage of the uncertain parameter range than random sampling. The issue of interdependence or statistical correlation between parameters is also important. The sampling algorithm used in the TSPA-SR and supplemental TSPA models, ensures that any desired correlation between input parameters is retained, while any spurious correlation that might arise because of the finite size of the sample is eliminated.

4. **Calculating the model outcome for each sample set and tallying the results for all samples**—In this step, scientists evaluate the model that describes the behavior of the system in the scenario of interest for each of the equally likely, randomly generated parameter sets. This is a simple operation consisting of multiple model calls, where the outcome (i.e., annual dose as a function of time) is computed for each sampled parameter set. Once all the required model runs have been completed, the overall uncertainty in the predicted outcome can be characterized by summary statistics, such as the mean and median, and/or by the cumulative probability distribution.

Incorporating Conceptual Model Uncertainty—Conceptual model uncertainty refers to an incomplete understanding of what processes dominate system behavior and how different processes might affect one another; in other words, conceptual model uncertainty reflects a state of imperfect or incomplete knowledge. Multiple conceptual models can be hypothesized that fit the empirical data equally well. Conceptual model uncertainty is addressed by evaluating plausible alternative conceptual models of process relationships. The conceptual model that best fits empirical data, when such a model exists, is used in the integrated TSPA model. When multiple conceptual models are plausible, either a conservative model is chosen or the models are weighted and combined, and the resulting combination is used in the integrated TSPA model. An alternative approach for incorporating conceptual model uncertainty is via a bounding model, such that the consequence can be "bounded." Note that conservative/bounding models are used as additional tools for representing uncertainty in the TSPA model, in addition to the detailed representation of parametric uncertainty via probability distributions.

Incorporating Scenario Uncertainty—Uncertainty related to future states arises because the geologic and environmental conditions occurring over thousands of years cannot be predicted with certainty. As a result, scenarios of plausible future system states (e.g., system changes arising from the evolution of the geologic setting) have been derived from scientific inferences drawn from direct and indirect field evidence from the Yucca Mountain site. Through the FEPs screening procedure, scenarios of system perturbations are conceptualized and characterized in terms of both likelihood of occurrence and potential impact on natural and engineered barriers. As discussed below, the scenarios have been organized into two groups: (1) nominal and disruptive conditions (e.g., repository heating, climate change, seismicity effects, igneous activity) and (2) human intrusion. These scenarios have been evaluated as part of the probabilistic TSPA and the associated consequences included in the projected annual doses.

As discussed, the TSPA done without human intrusion analyzes two scenarios—the nominal and disruptive events scenarios. The mean dose for each of these scenarios was probability-weighted and summed to calculate the dose to the receptor (i.e., the average member of the critical group for the TSPA-SR model analyses and the reasonably maximally exposed individual for the revised supplemental TSPA model).

Presentation of Results—The data from the multiple realizations are graphically summarized by showing time versus annual dose (i.e., annual dose histories) for all realizations (i.e., 300 realizations for the nominal case and 5,000 realizations for the igneous-activity scenario). Graphical representations that display all the realizations of the output from the multiple-realization simulations are termed "horsetail plots." These results of the multiple-realization simulations can be displayed along with statistical measures of the output. Typically, the graphical representations show the mean and the median of the output along with 5th and 95th percentile of the output. In the same manner as described for *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a, Section 2.2.4.6, pp. 2-39 to 2-40), these statistical measures are calculated using the data from all realizations of the probabilistic simulations at each time step of the dose histories. The plot of the mean represents the arithmetic average of data points from each realization at each time step. For each point on the plot of the median dose, 50 percent of the data have a value greater than the plotted point and 50 percent have a value less than the plotted point. Likewise, for the 95th and 5th percentiles, the plotted data points are such that 5 percent of data are greater (or less) than the plotted point and 95 percent of the data points are less (or greater) than the plotted points, for each point, or time step, plotted. The statistical measures can be superimposed in contrasting colors on the horsetail plots (Williams 2001a).

4.4.1.3 Treatment of Potentially Disruptive Scenarios

Evaluation of the postclosure performance of a potential geologic repository at the Yucca Mountain site considers disruptive processes and events important to the total system performance of the geologic repository. These disruptive processes and events include (1) volcanism; (2) seismic events; (3) nuclear criticality; and (4) inadvertent human intrusion. These processes have been examined through the FEPs screening process. The results include the following observations:

- Volcanism (including an igneous intrusion that does not erupt at the surface) has occurred in the Yucca Mountain region in the past. Current evaluations indicate a probability of recurrence slightly more than 1 chance in 10,000 during the next 10,000 years. Therefore, the TSPA models explicitly consider the impact of volcanism in a subsystem model. The TSPA treatments for the two volcanic disruption scenarios are described in Sections 4.4.1.3.1 and 4.4.1.3.2. The TSPA results for these scenarios are described in Section 4.4.3.

- Most impacts of seismic events have been excluded from the TSPA on the basis of insignificant consequence or low probability. More specifically, seismic changes in hydrology (including seismic pumping) are not great enough to have a significant effect on overall performance; seismically induced rockfall will not be large enough to degrade the drip shield and waste package significantly; and the probability of fault displacement within the repository is below 1 chance in 10,000 of occurring over 10,000 years. Because vibratory ground motion from seismic events of uncertain magnitude is likely to occur at Yucca Mountain in the future and might damage the spent nuclear fuel cladding, the effect of this potential damage to cladding by a discrete seismic event is included in the TSPA model in the nominal scenario (rather than the disruptive scenario). The frequency assumed for this event is 1.1×10^{-6} per year. For the analysis, when the vibratory ground motion event occurs, all commercial spent nuclear fuel cladding in the repository is assumed to fail by perforation, and further cladding degradation is calculated according to the cladding degradation model.

- The DOE has considered postclosure criticality using the risk-informed methodology described in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2000c). The NRC had issued a Safety Evaluation Report (Reamer 2000) for the initial postclosure criticality methodology (YMP 1998) with a few open items. The postclosure criticality methodology has been updated in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2000c) to address the open items. This assessment included consideration of site characteristics relevant to criticality as determined by a comprehensive assessment of site data and information obtained during site characterization. Three potential criticality scenarios were considered for the TSPA: (1) inside one or more degraded waste packages; (2) in rock surrounding emplacement drifts, as a result of the transport of fissile materials from degraded waste packages; and (3) in rock at some distance from the emplacement drifts, as a result of the accumulation of fissile materials under favorable conditions.

  The results from these analyses indicate that the probability of a criticality in the 10,000 years is less than 1×10^{-4} for all commercial pressurized water reactor spent nuclear fuel waste packages (Section 4.3.3.2.3). This low probability is expected to apply to all waste forms placed in a potential repository. Additional scenarios, including criticality without the presence of water and autocatalytic criticality, were considered and eliminated from further consideration because the probabilities of such events are so low that they are not credible. Criticality external to the waste package would require sufficient water flux to carry substantial amounts of fissile materials from breached waste packages to a location in the rock with favorable conditions for accumulating large amounts of fissile material. Lower water flux would mean a lower probability of this phenomenon occurring. Potential early waste package failures from improper heat treatment are modeled to fail by cracking in the closure weld areas. This failure mode, along with the existence of an intact drip shield, would not allow significant water flux through the waste package, thereby reducing the probability of a criticality event. Section 4.3.3.2 provides a brief description of the methodology and results from this analysis.

- Human intrusion has been analyzed in a stylized scenario. Section 4.4.4 presents the results of the TSPA-SR model and supplemental TSPA model analysis. Human intrusion is not included in either the nominal or disruptive scenarios, and the consequences of human intrusion are not included in the estimates of performance presented in Sections 4.4.2 and 4.4.3.

Analyses of these disruptive processes have been performed by the TSPA-SR model and the supplemental and revised supplemental TSPA models. Detailed results of these analyses are presented in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a), *FY01 Supplemental Science and Performance Analyses* (BSC 2001a; BSC 2001b), and *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a).

The treatment of potentially disruptive scenarios associated with volcanism addresses models for two types of disruption of the repository: volcanic eruptions that intersect drifts and bring waste to the surface and igneous intrusions that damage waste packages and expose radionuclides for groundwater to transport. These two types of disruption were described in the *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998, Volume 3, Section 4.4) as the direct release scenario and the enhanced source term scenario, respectively. Descriptive terms used for these scenarios are volcanic eruption and igneous intrusion groundwater transport, respectively. These terms, as well as combined igneous activity, are used in the reports documenting the results of TSPA analyses of disruptive events (BSC 2001a; BSC 2001b; Williams 2001a; Williams 2001b). This treatment of volcanism does not address the indirect effects of igneous activity that does not intersect the repository. As described in *Features, Events, and Processes: Disruptive Events* (CRWMS M&O 2000ex), the indirect effects of igneous activity are shown to have such small consequences that they are not included in TSPA-SR estimates of overall system performance.

The treatment of potentially disruptive scenarios draws extensively on activities performed specifically to define the disruptive events to be modeled in the TSPA and to provide the distributions assigned to parameters. In addition, full implementation of the igneous consequence models in the TSPA-SR model and supplemental TSPA models also requires information from other sources. Figure 4-175 shows the relationship among the major products developed specifically to support the igneous consequence modeling and shows how these products support each other and the TSPA analyses. The reports associated with analyses, models, and calculations performed explicitly to address the disruptive scenarios are shown in this figure in boxes with solid lines. Reports from activities that provide other inputs into the TSPA necessary to evaluate the consequences associated with the disruptive scenarios are shown in dashed boxes.

Characterize Framework for Igneous Activity at Yucca Mountain, Nevada (CRWMS M&O 2000ez) provides basic information about volcanic activity in the Yucca Mountain region and derives the probability of future volcanic activity from information provided in *Probabilistic Volcanic Hazard Analysis of Yucca Mountain, Nevada* (CRWMS M&O 1996b). Information from this analysis about the general nature of volcanic activity in the Yucca Mountain region is also used in *Characterize Eruptive Processes at Yucca Mountain, Nevada* (CRWMS M&O 2000fa) to support detailed characterization of the events and processes associated with a volcanic eruption. *Dike Propagation Near Drifts* (CRWMS M&O 2000fb) provides an estimate of the extent of damage to waste packages near an intrusive dike. Information from these three reports is used in *Number of Waste Packages Hit by Igneous Intrusion* (CRWMS M&O 2000fi) to support the calculation of cumulative distribution functions that characterize the number of

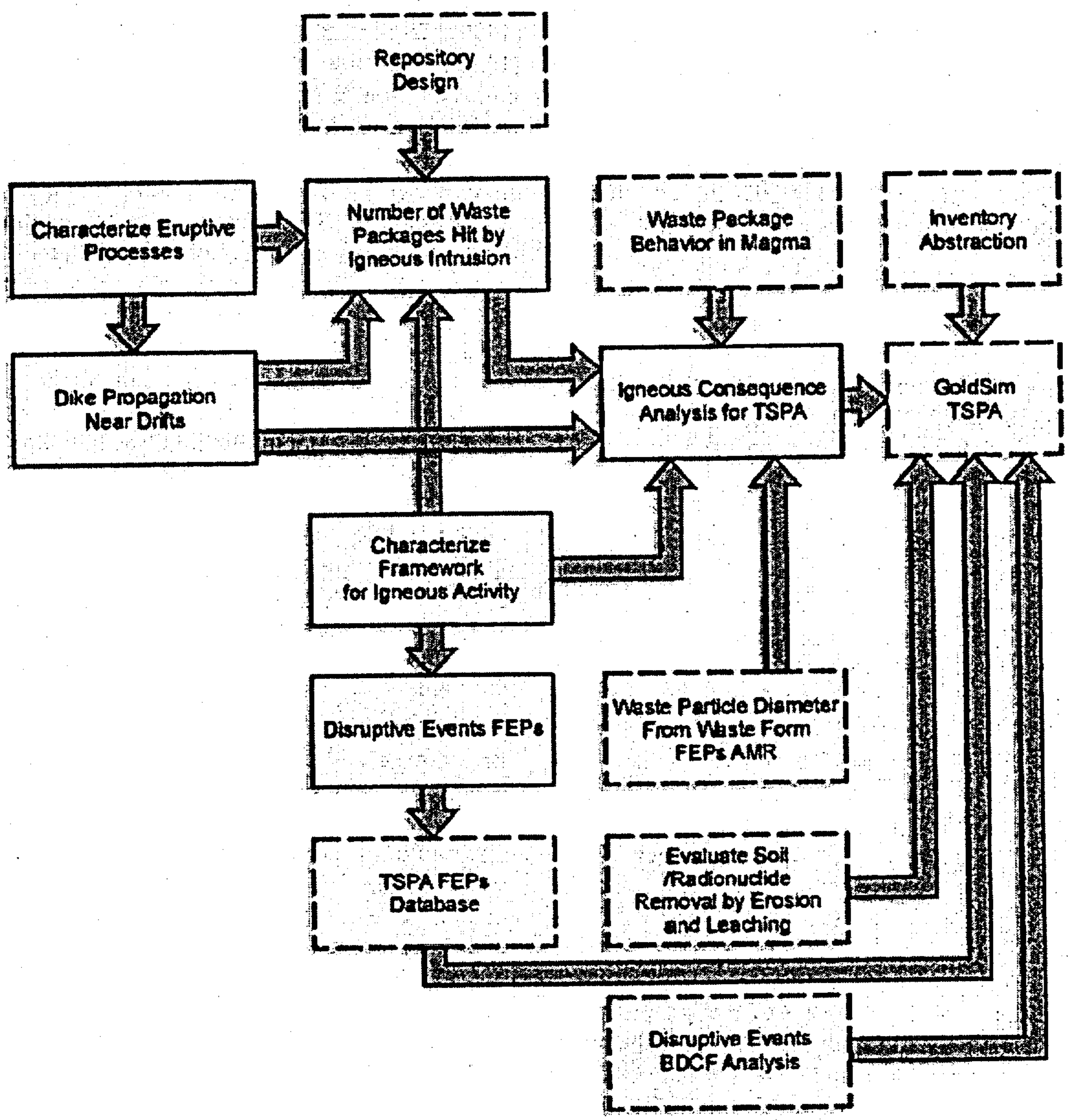


Figure 4-175. Information Feeds to Igneous Consequence Modeling in the Total System Performance Assessment

Reports from activities that provide other inputs into the TSPA necessary to evaluate the consequences associated with the disruptive scenarios are shown in dashed boxes. AMR = analysis model report; BDCF = biosphere dose conversion factor.

waste packages affected by intrusions and eruptions. As shown in Figure 4-175, *Igneous Consequence Modeling for the TSPA-SR* (CRWMS M&O 2000fc) draws information from *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* (CRWMS M&O 2000ez), *Characterize Eruptive Processes at Yucca Mountain, Nevada* (CRWMS M&O 2000fa), *Number of Waste Packages Hit by Igneous Intrusion* (CRWMS M&O 2000fi), *Miscellaneous Waste-Form FEPs* (CRWMS M&O 2000eu), and *Waste Package Behavior in Magma* (CRWMS M&O 1999p).

4.4.1.3.1 Volcanic Eruption Scenario

Igneous Consequence Modeling for the TSPA-SR (CRWMS M&O 2000fc) evaluated three models for evaluating volcanic eruptions and concluded that the volcanic eruption scenario should be modeled in the TSPA-SR model using the code ASHPLUME (CRWMS M&O 2000fc, Section 6.1). ASHPLUME has also been used by the supplemental TSPA models (BSC 2001a; BSC 2001b). This recommendation is based on the relative maturity of the model and code and the wide acceptance of the underlying Suzuki model. The ASHPLUME code was developed at the Center for Nuclear Waste Regulatory Analyses sponsored by the Southwest Research Institute. The Center is assisting the NRC in assessing site characterization and long-term safety at the proposed Yucca Mountain site. The ASHPLUME code implements the Suzuki igneous model (Suzuki 1983), a mathematical implementation of an atmospheric dispersal model. The Suzuki model does not attempt to model the subsurface physics of the igneous event but relies on expert inputs for the physical characteristics of the volcano and models the atmospheric dispersal of the ash particles downwind until the ash settles on the ground. The modified ASHPLUME code used for TSPA models added the coupling of waste particles to the ash particles to model a volcanic igneous event through the potential repository. The resulting model maintained all the physical characteristics of the Suzuki model (Suzuki 1983).

The TSPA-SR implementation of the ASHPLUME model is the same as the TSPA model in the VA, with improvements in the input parameter values. Engineers obtained the current input parameter values from the reports and calculations referenced earlier in this section, as well as Jarzemba et al. (1997); Lide (1994); Suzuki (1983); Reamer (1999); Wilson, L. and Head (1981); and Quiring (1968). One key additional improvement is the model for the intersection of a conduit with the repository drifts in *Number of Waste Packages Hit by Igneous Intrusion* (CRWMS M&O 2000fi) and *Waste Package Behavior in Magma* (CRWMS M&O 1999p). This allows a more complex, detailed analysis of the number of drifts and waste packages that would be intersected by one or more conduits, which provides a means of tracing the justifications behind the input values and allows for an improved accountability for their use.

4.4.1.3.2 Igneous Intrusion Groundwater Transport Scenario

The igneous intrusion groundwater transport scenario evaluates the effect of an igneous intrusion on waste packages in the drifts. For this scenario, the affected waste packages are modeled as compromised to the extent that the waste form inside is completely exposed (i.e., the waste package and cladding have been severely degraded or destroyed). After the magma cools, groundwater begins to flow through the zone with the flow characteristics and transport properties described in the unsaturated zone flow model; on reaching the water table, the transport continues under the conditions described by the saturated zone flow and transport model.

Table 4-35 summarizes the igneous intrusion groundwater event input parameters recommended in *Igneous Consequence Modeling for the TSPA-SR* (CRWMS M&O 2000fc). The table lists the input parameter, the format of the input parameter, and the input data source.

Additional assessments evaluated the effect on dose of the volcanic eruption scenario and the igneous intrusion groundwater transport scenario. Results are documented in Volume 2, Section 4.3.1 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b). Revised supplemental analyses are reported in *Total System Performance*

Table 4-35. Igneous Intrusion Groundwater Event Scenario Input Parameters

Input Parameter	Input Parameter Format	Addressed In
Event Probability	Cumulative Distribution Function	CRWMS M&O 2000ez, Section 6.5.1.3
Percentage of Hit Packages that Fail	Assume 100%	CRWMS M&O 1999p
Number of Packages Hit	Cumulative Distribution Function	CRWMS M&O 2000fi, Figure 1-8

NOTES: CRWMS M&O 1999p: *Waste Package Behavior in Magma.*
CRWMS M&O 2000ez: *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada.*
CRWMS M&O 2000fi: *Number of Waste Packages Hit by Igneous Intrusion.*

Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation (Williams 2001a, Section 6.3). These results are presented in Section 4.4.3 of this report.

4.4.1.4 Summary of Radionuclides of Concern Considered in Dose Assessment

The purpose of the TSPA models is to investigate the potential for and impact of radionuclides escaping a potential repository at Yucca Mountain. Many radionuclides only exist for microseconds, and some do not contribute significantly to potential dose. There are hundreds of radionuclides in the waste inventory, and some will be created and destroyed in the cascading process of radioactive decay and ingrowth. It is not practical to numerically portray the behavior of all these radionuclides, their daughter products, and their progeny. Instead, a screening approach was used to identify those radionuclides that would contribute significantly to the potential dose to a receptor living in the vicinity of Yucca Mountain. The most significant contributors to potential dose are included in the TSPA models; these account for at least 95 percent of the potential dose. This section summarizes the screening process. The result of this process—a list of radionuclides—is an important part of the TSPA analyses discussed in the rest of this report.

Radionuclide Screening Based on Contribution to Dose—The metric for screening radionuclides for the TSPA models is the radiation dose that a radionuclide could impose on a human living in the vicinity of Yucca Mountain. A methodology has been developed that identifies the important dose contributors, based on an estimate of the amounts of radionuclides that could reach a human receptor (CRWMS M&O 2000ds). Identification of the important dose contributors involves three steps:

1. For the waste form under consideration, the relative dose contribution from an individual radionuclide is calculated by multiplying its inventory abundance (in terms of its radioactivity) by its dose conversion factor (a number that converts an amount of a radionuclide into the dose that a human would incur if the radionuclide were exposed to, ingested, or inhaled). This multiplication gives a result that is not significant by itself; however, when it is compared to values derived in the same manner for other radionuclides in the waste form, the radionuclide that is the more important contributor to the dose can be determined.

2. The individual radionuclides are ranked, with the highest contributor to the dose given the highest ranking, and the percent contribution of each radionuclide in the list to the total dose (the sum of the doses from the radionuclides in the list) is calculated.

3. Radionuclides that are included in the TSPA models are the highest-ranked radionuclides that, when their dose contributions are combined, produce at least 95 percent of the potential dose.

These steps identify which radionuclides would be included in the dose estimate, should all radionuclides in a waste form be released to the environment in proportion to their inventory abundance. However, radionuclides are not always released in proportion to their inventory abundance. Factors that can affect releases of radionuclides, depending on the scenario being considered, include radionuclide longevity, solubility, and transport affinity.

Radionuclide longevity is the lifetime of a radionuclide before it decays. Solubility is the amount of a radionuclide that will dissolve in a given amount of water. Transport affinity is a radionuclide's potential for movement through the environment. This movement can involve a number of mechanisms, for example: fracture flow (the advective movement of radionuclides with water flowing in fractures), matrix diffusion (the diffusion of radionuclides from water in the fractures into water in the matrix), or colloid-facilitated transport (the movement of radionuclides associated with small particles of rock or waste form degradation products). Transport affinity is not a measurable property but a qualitative description of the likelihood of transport. If a group of radionuclides is transported via a particular mechanism, and that mechanism dominates release, the group of radionuclides will be preferentially released (relative to radionuclides not in the group) to the environment. If a radionuclide has a short half-life, it will have a higher activity in the waste form at early times (close to repository closure); however, at later times, the radionuclide will have all but disappeared from the waste form. If a radionuclide is not soluble in the near-field environment around the waste package, it may not be released to the environment through groundwater transport, even if it is abundant and available.

Because radionuclide longevity, solubility, and transport affinity can affect releases of radionuclides, the identification of important dose contributors includes examination of possible "what-if" scenarios that could result in releases of radionuclides to the environment. For example, "What if radionuclide releases are the result of a colloidal transport mechanism?" If the steps described previously are applied to the subset of radionuclides that could be released through a colloidal transport mechanism (radionuclides that readily bind to rock and colloidal particles), which of those radionuclides would be identified as the important contributors to dose?" Or, "What if a volcanic direct release to the environment occurs?" If the steps described previously are applied to the radionuclides present in the waste form involved in a direct release, which of those radionuclides would be identified as the important contributors to dose?" The radionuclide screening examined over 1,200 potential what-if scenarios and identified the important dose contributors for each one. The cases examined consider times from 100 years to 1 million years after repository closure (100, 200, 300, 400, 500, 1,000, 2,000, 5,000, 10,000, 100,000, 300,000, and 1 million years); eight waste forms (average and bounding pressurized water reactor fuel, average and bounding boiling water reactor fuel, average and bounding DOE spent nuclear fuel, and average and bounding DOE high-level radioactive waste) three transport affinity groups (highly sorbing, moderately sorbing, and slightly to nonsorbing); and two exposure pathways (inhalation and ingestion).

As noted previously, the radionuclides considered in calculating potential dose to the reasonably maximally exposed individual living in the vicinity of Yucca Mountain were selected based on their contribution to dose. The importance of a particular radionuclide is also related to pathway and time of release. Table 4-36 lists the radionuclides considered for three release scenarios, summarizing the differences in importance of particular radionuclides relative to the pathway and time of release for these scenarios. The supplemental TSPA models used the same radionuclides in their analyses (BSC 2001a; BSC 2001b; Williams 2001a). A direct volcanic release scenario involves pathways (e.g., inhalation) that can be different from those modeled in the nominal scenario. If a radionuclide is important for estimating the dose from DOE spent nuclear fuel, it is included in the TSPA models, even though these waste forms would occupy a small fraction of the repository. Similarly, if a radionuclide is important for estimating the dose from the highly sorbing transport group, it is included in the TSPA models, even if analyses show that colloid transport is a minimal contributor to release.

Consideration of Decay Chains and Transport Characteristics—In addition to the radionuclides selected based on contribution to dose, other

Table 4-36. Radionuclides Selected for Consideration in Total System Performance Assessment–Site Recommendation Based on Contribution to Dose

Isotope	Direct Volcanic Release Scenario	Nominal Scenario			Human Intrusion		
		Strongly Sorbing	Moderately Sorbing	Slightly to Nonsorbing	Strongly Sorbing	Moderately Sorbing	Slightly to Nonsorbing
Actinium-227	X	X			X		
Americium-241	X	X			X		
Americium-243	X	X			X		
Carbon-14				X			X
Cesium-137[b]	X				X		
Iodine-129				X			X
Neptunium-237			X			X	
Protactinium-231	X	X[a]			X[a]		
Lead-210	X[a]	X[a]			X[a]		
Plutonium-238	X	X			X		
Plutonium-239	X	X			X		
Plutonium-240	X	X			X		
Plutonium-242	X[a]	X[a]			X[a]		
Radium-226	X[a]	X[a]			X[a]		
Strontium-90[b]	X				X		
Technetium-99				X			X
Thorium-229	X	X			X		
Thorium-230	X[a]	X[a]			X[a]		
Uranium-232	X		X			X	
Uranium-233	X		X			X	
Uranium-234	X		X			X	
Uranium-236			X			X	
Uranium-238			X			X	

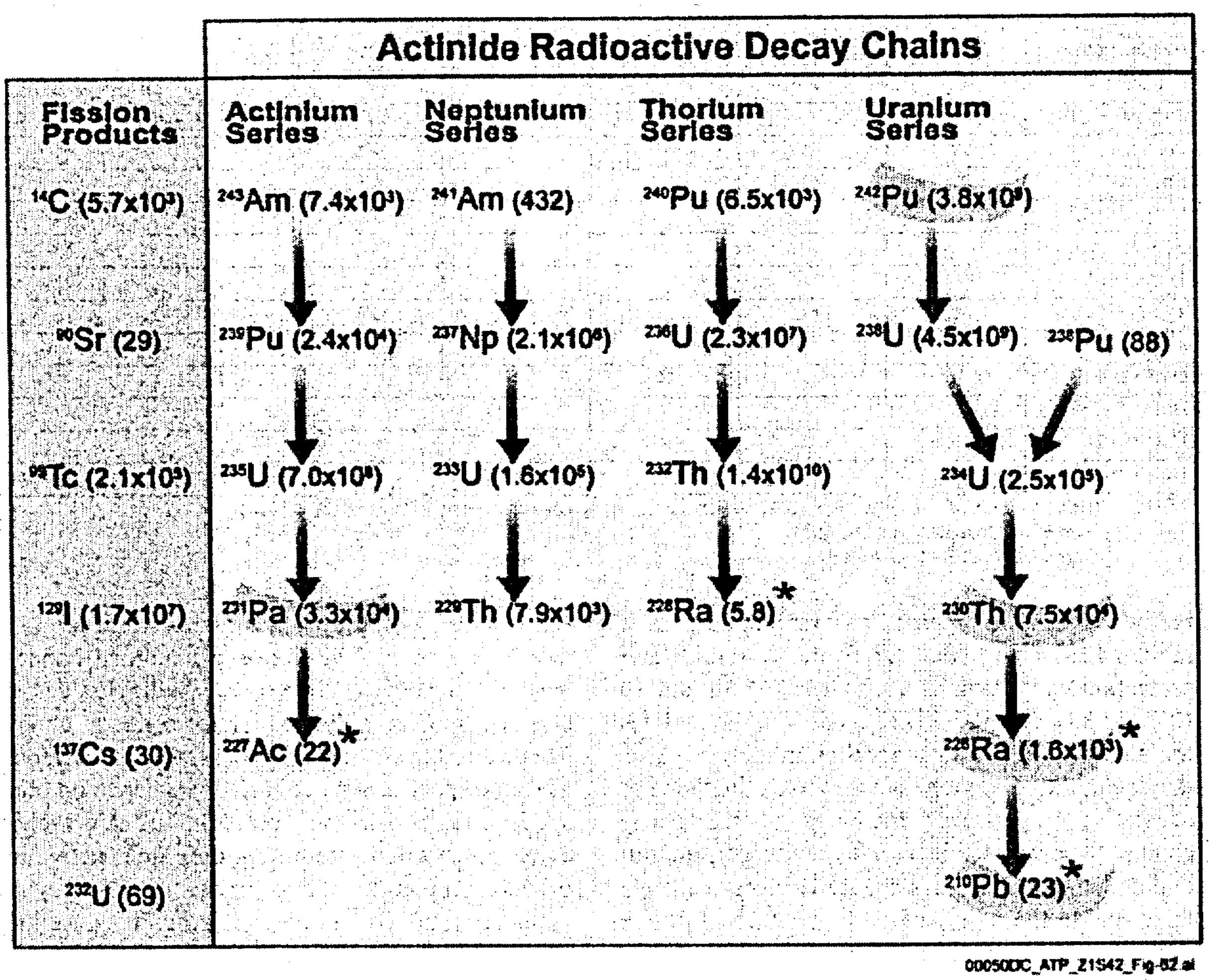
NOTES: [a]Important for calculations after 10,000 years, specifically peak-dose calculations (DOE 1999a).
[b]Not included in nominal scenario.
Source: CRWMS M&O 2000ds.

radionuclides (in particular radium-226 and radium-228) are considered for groundwater protection consistent with 40 CFR 197.30 and 10 CFR 63.331 (66 FR 55732). Other radionuclides are also considered in the TSPA models because they belong to decay chains; they were included to accurately track other members of the decay chains. (A decay chain is a sequence of radionuclides that, because of radioactive decay, change from one to the other; thus, the amount of one is dependent on the amounts of the others.)

The radionuclides selected for consideration in the TSPA models fall into two basic categories: fission products (plus carbon-14 and uranium-232) and actinides (plus lead-210 and radium isotopes). Fission products are the lighter elements that result when the heavier, fissionable elements that constitute nuclear fuel, primarily uranium-235, are split to release energy. The fission products of concern here do not decay into other radionuclides of concern; that is, they do not form decay chains. Therefore, the fission products can be considered as single species, with no interdependence on other species. Carbon-14 and uranium-232 are technically not fission products—they are activation products formed by neutron capture— but they are included in the fission-product group because they are not members of decay chains.

The actinide group includes the heavy elements that comprise nuclear fuel and the heavy-element by-products formed by neutron capture or decay of these elements (including lead and radium). The actinides typically decay by losing an alpha particle. Therefore, they tend to form decay chains in which the isotopes are spaced by an atomic weight of four. For example, uranium-238 loses an alpha particle and decays to uranium-234, which similarly decays to thorium-230, etc. (The actual radionuclide decay chains are much more complicated than this explanation suggests, involving not only alpha radiation, but also beta, gamma, and neutrino radiation and, typically, many intermediate products. However, the significant chain members—those that exist for relatively long times—are separated primarily by release of an alpha particle.) For the actinides that are important to dose, the decay of parent radionuclides (those higher in the decay chain) and the ingrowth of daughter radionuclides (those lower in the chain) must be tracked during transport.

Figure 4-176 shows the complete list of the radionuclides considered in the TSPA-SR, including how the radionuclides considered in the TSPA-SR are related by membership in decay chains. What follows is a brief discussion of each radionuclide modeled in the TSPA-SR, and—because how radionuclides are modeled in the TSPA-SR depends, to



Important to peak-dose calculations only

* Calculated by assuming secular equilibrium

Figure 4-176 All Radionuclides Considered in the TSPA model, Showing Decay-Chain Relationships (with Half-Lives in Years)
Source: Modified from CRWMS M&O 2000a, Figure 3.8-13.

a certain extent, on radionuclide-specific characteristics—the radionuclide-specific characteristics that are important to modeling the radionuclide in the TSPA-SR. These include the half-life and the transport mechanism. This discussion is summarized from Section 3.5 of *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a). The same radionuclides were considered in the supplemental TSPA model and the revised supplemental TSPA model. Detailed information can be found in *FY01 Supplemental Science and Performance Analyses* (BSC 2001a; BSC 2001b) and *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a).

Fission Products—Carbon-14 is a relatively nonsorbing radionuclide with a short half-life that moves easily in groundwater; as such, it is tracked in the human intrusion analysis and the nominal scenario. Carbon-14 does not contribute substantially to dose at periods after 10,000 years and is not considered in the post-10,000-year analyses. Carbon-14 transports as solute. Strontium-90 and cesium-137 are both strongly sorbing radionuclides with short half-lives. Although the initial inventory of the repository would contain substantial amounts of these radionuclides, they are only important to dose if they are released at very early times and transported rapidly. Because early release and rapid transport are not expected, these radionuclides are only considered for direct volcanic and human intrusion releases. Strontium-90 and cesium-137 are relatively immobile in groundwater, except perhaps when associated with colloids; to respect this possibility, colloid-facilitated transport of these radionuclides is considered in the TSPA models. Technetium-99 and iodine-129 are radionuclides with relatively long half-lives that are fairly mobile in groundwater; they are considered for all analyses except direct volcanic releases, in which case they are not important because they do not constitute a large part of the initial inventory. Technetium-99 and iodine-129 transport as solute. Uranium-232 is a radionuclide with a short half-life that is sufficiently present in the initial inventory to be important to inhalation dose if released early enough; therefore, it is considered in the direct volcanic release scenario.

Actinium Series—Americium-243, plutonium-239, and actinium-227 are important to dose in all analyses. Uranium-235 and protactinium-231 are not important to dose, but both are followed to track actinium-227. Americium-243 and plutonium-239 are both strongly sorbing and only transport when associated with colloids. Uranium-235 is only moderately sorbing and thus transports as solute. Protactinium-231 is a strongly sorbing radionuclide and is relatively immobile, except perhaps when associated with colloids; as with strontium-90 and cesium-137, to respect this possibility, colloid-facilitated transport of protactinium-231 is considered in the TSPA-SR. Actinium-227, because of its brief lifetime, is assumed to be in secular equilibrium with protactinium-231. (Secular equilibrium is when a daughter radionuclide has reached a steady-state amount, in terms of radioactive activity, with respect to the amount of its parent radionuclide. The secular-equilibrium assumption tends to overestimate the amount of a daughter product when there is no significant daughter source; in this regard, it is typically a conservative assumption.)

Neptunium Series—Americium-241, neptunium-237, uranium-233, and thorium-229 are important to dose in all the analyses, except that americium-241 is not important to the long-term performance because of its relatively short half-life. Americium and thorium are only transported when associated with colloids. Neptunium and uranium are transported as solute. The amount of americium-241 is increased to account for ingrowth from the very short-lived plutonium-241.

Thorium Series—Plutonium-240 and uranium-236 are important to dose in all analyses, except that uranium-236 is not important in direct volcanic releases and plutonium-240 is not important past 10,000 years because of its relatively short half-life. Thorium-232 is considered only because it is part of the decay chain that generates radium-228. Radium-228 is specified by the proposed and final EPA regulation for groundwater protection. Plutonium and thorium are transported only when associated with colloids; uranium is transported as solute. Because of its short half-life, radium-228 is considered to be in secular equilibrium with thorium-232 in the TSPA models.

Uranium Series—The radionuclides selected for consideration in the TSPA-SR are shown in Table 4-36. Plutonium-242 is only important to long-term repository performance analysis. Plutonium-238 is important to all analyses except the longer time-period peak-dose analysis (because of its short half-life). The plutonium isotopes are only transported when associated with colloids. Uranium-238 is important to nominal-scenario dose, primarily because of its tremendous inventory in the repository. Uranium-234 is important to all analyses. The uranium isotopes are mobile as solute. Thorium-230 is only important to dose in long-term repository performance analysis, but must be tracked in the groundwater protection analysis to complete the uranium series decay chain. Thorium is only transported when associated with colloids. Radium-226 is important to long-term repository performance analysis, direct volcanic release analysis, and the groundwater protection analysis. Radium-226 has a short half-life and, for simplicity, is assumed to be in secular equilibrium with thorium-230 (Parrington et al. 1996).

4.4.2 Total System Performance for the Nominal Scenario

This section summarizes the TSPA-SR model and supplemental TSPA models' postclosure performance assessment results for the nominal scenario. The nominal scenario is used for calculations of the groundwater radionuclide activity concentrations and dose to the whole body (or any critical organ) for groundwater protection. The dose projected for the nominal scenario is also combined with the probability-weighted dose from the disruptive scenario for individual protection consistent with 40 CFR Part 197 and 10 CFR Part 63 (66 FR 55732).

Following a discussion of the elements of the nominal scenario in Section 4.4.2.1, the nominal performance results for dose to the hypothetical receptor are presented in Section 4.4.2.2. The nominal performance results for the groundwater concentrations are presented in Section 4.4.2.3. In addition, Section 4.4.2.4 presents the projected results of postclosure performance during the time period of geologic stability, also presented in *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE 2002) (see 40 CFR 197.35 and 10 CFR 63.341 [66 FR 55732]).

The postclosure performance measures applicable to the Yucca Mountain repository system extend to a time period of 10,000 years after repository closure. An important element of the DOE repository safety strategy (CRWMS M&O 2001a, Volume 2) is the use of a safety margin to offset uncertainties associated with the analyses used to demonstrate compliance with the postclosure performance objective. The safety margin considered by the DOE has two components: (1) the margin in the dose rate during the first 10,000 years and (2) the margin over time periods greater than 10,000 years. To address the second element of the safety margin, analyses have been conducted to 100,000 years after repository closure. These analyses are performed to provide insights into the robustness of the repository system performance (CRWMS M&O 2001a, Volume 2, Section 5.2.1). In addition to these 100,000-year analyses, analyses out to the peak dose during the time period of geologic stability (1 million years) have been conducted. These analyses are described in Section 4.4.2.4.

4.4.2.1 Definition of the Nominal Scenario

The nominal scenario includes all relevant FEPs that are expected to occur over 10,000 years following the closure of the repository after emplacement of the waste packages. The nominal scenario is distinguished from the potentially disruptive scenario described in Section 4.4.3. In the nominal scenario, the expectation is that the processes included in the analyses are anticipated to occur with a probability of close to one within the 10,000-year time period, while the probability of events for the disruptive scenario is on the order of 0.0001 over the 10,000-year period.

TSPAs are projections of the behavior of individual processes described by distinct component models. These projections describe the relevant processes affecting the containment and isolation of radioactive wastes from the biosphere. Uncertainty is explicitly included in the models and the resulting analyses in the form of discrete probability distributions that encompass the range of possible outcomes. In the results presented in this section, uncertainty in the possible performance is evaluated through the use of these probabilistic analyses. Although the expected or mean performance of the repository system can be determined from the range of probabilistic outcomes, this section focuses on examining the full range of possible outcomes and the probability of each projected performance occurring.

The nominal scenario consists of models and parameters of the processes described in Section 4.2. The principal process models for the nominal scenario may be grouped into four key attributes of postclosure safety for the Yucca Mountain repository system. A fifth attribute reflects the likelihood that disruptive events would not affect repository performance over 10,000 years. The attributes and the principal process models within each attribute are:

- **Limited water entering emplacement drifts**—includes models describing climate, infiltration, unsaturated zone groundwater flow, water seepage into drifts, and the effects of thermal hydrology on groundwater flow and seepage.

- **Long-lived waste package and drip shield**—includes models describing the effects of the in-drift geochemical, thermal, hydrologic, and mechanical environments on the drip shields and waste packages, as well as the degradation characteristics of the titanium drip shield and the Alloy 22 waste package.

- **Limited release of radionuclides from the engineered barriers**—includes models describing the alteration of the different radioactive waste forms, as well as the mobility of the wastes in either dissolved or colloidal form.

- **Delay and dilution of radionuclide concentration by the natural barriers**—includes models describing (1) the retention and transport of different radionuclide species in the unsaturated zone beneath the repository, (2) radionuclide transport through the saturated zone, and (3) the biosphere pathways that may bring dissolved radionuclides into contact with humans.

- **Low mean annual dose considering potentially disruptive events**—includes models describing the probability and consequences of igneous or volcanic intrusions into or near the repository, with potential radionuclide releases through enhanced groundwater transport pathways or through airborne volcanic eruption pathways.

Models of all the above processes are integrated into the TSPA, as illustrated in Figures 4-177 and 4-178. These figures illustrate how information flows within the context of the TSPA model. The model is used to predict how the integrated and interdependent processes evolve over time and space, following the emplacement of the waste packages and drip shields and the ultimate closure of the repository. *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a) contains a detailed description of the TSPA-SR model.

FY01 Supplemental Science and Performance Analyses (BSC 2001a; BSC 2001b) describes the supplemental TSPA model, and *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a) describes the revised supplemental TSPA model.

Each of the component models included in the TSPA models directly quantifies the uncertainty in the underlying process or bounds that uncertainty appropriately by selecting parameters that bound potential consequences of the model from an

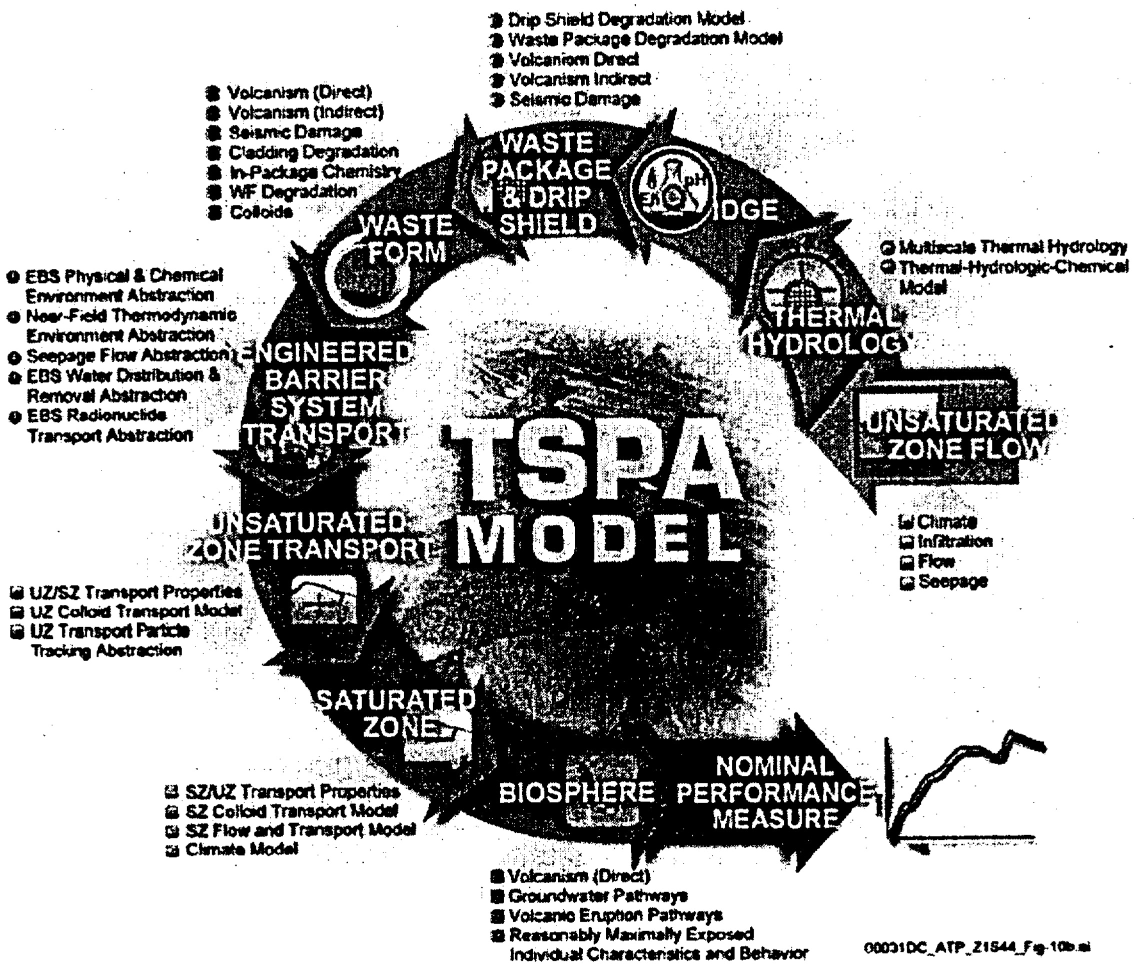


Figure 4-177. Component Models and Information Flow in the Total System Performance Assessment Model
IDGE = in-drift geochemical environment; WF = waste form; EBS = engineered barrier system; UZ = unsaturated zone; SZ = saturated zone.

overall performance perspective (i.e., that bound the expected dose to the receptor). The choice of whether a model or parameter directly incorporates the quantified uncertainty in the TSPA or uses reasonably conservative bounds was based on the availability of data. In cases where the uncertainty could be reasonably quantified with a sound scientific basis, the preferred option was to include this uncertainty directly in the TSPA model. In cases where the uncertainty could not be reasonably quantified as a probability distribution or alternative model, the analyst or modeler chose bounding conditions. The technical descriptions in Section 4.2, the nine process model reports, and Section 3 of the *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a) present detailed discussions of the basis for the uncertainty that is contained in the models and analyses.

Volume 1, in its entirety, and Volume 2, Section 3 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a; BSC 2001b) further discuss uncertainty and the quantification of previously unquantified uncertainty.

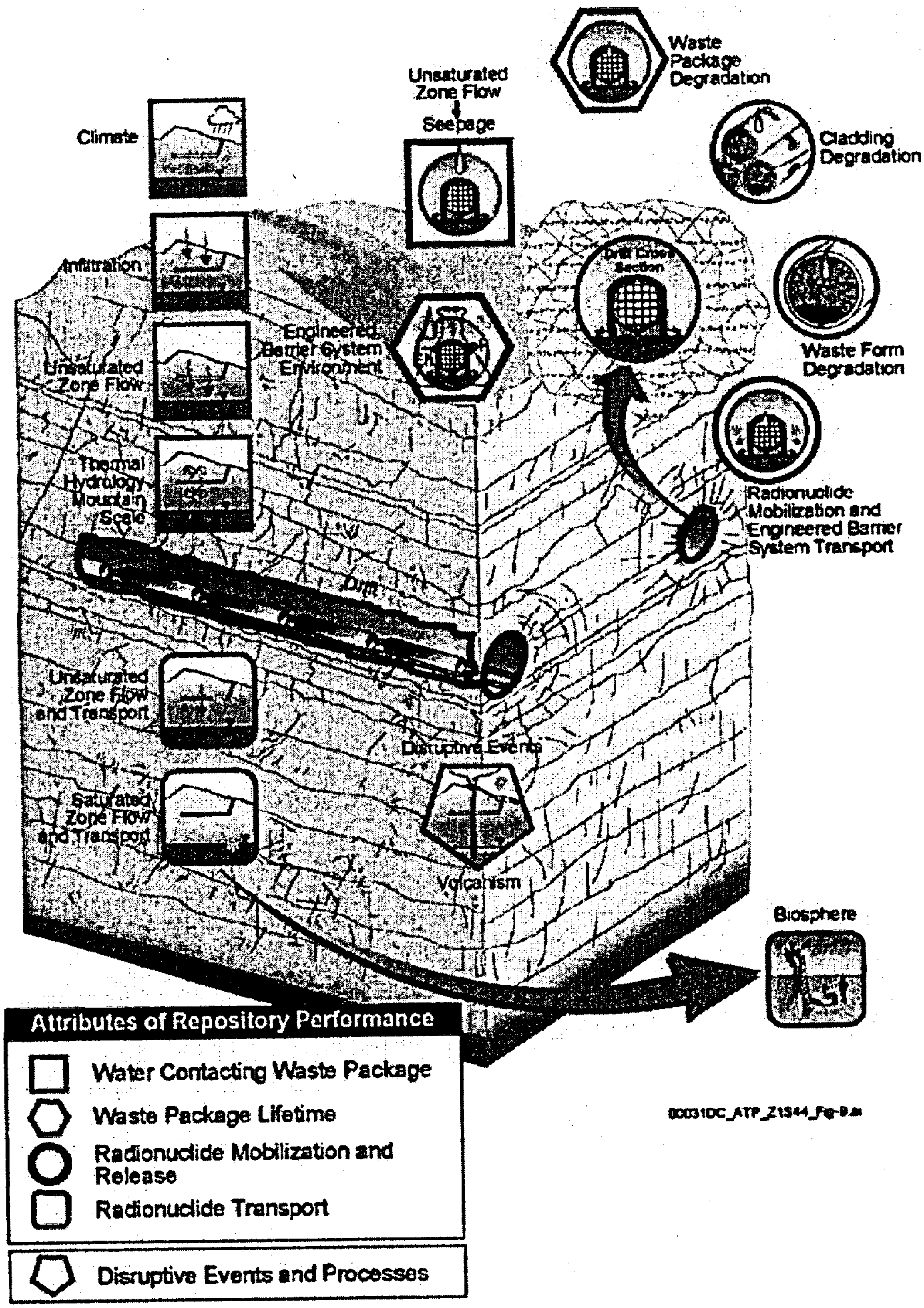


Figure 4-178. Component Models in the Total System Performance Assessment Nominal Scenario Model

In addition to grouping the process models into the different key attributes of postclosure safety, it is also worthwhile to briefly describe the component models in the sequence that represents the evolution of the repository system following the emplacement of the waste packages. This sequence essentially describes the processes that occur that ultimately lead to a release of radionuclides from the engineered barriers (e.g., after the containment provided by the waste packages has been breached) and the transport of these radionuclides to locations that they may come into contact with humans. The nominal scenario TSPA model evaluates the following sequence of processes:

- The temporal and spatial evolution of the physical and chemical environments on the engineered barriers (notably the drip shields and waste packages)
- The degradation of the engineered barriers within this range of possible physical and chemical environments
- The physical and chemical environments within the waste packages once the primary containment has been degraded to the point that throughgoing cracks penetrate the waste package
- The alteration rate of the waste form within the waste package, whether it is commercial spent nuclear fuel, DOE spent nuclear fuel (including naval spent nuclear fuel), or high-level radioactive waste, including immobilized plutonium waste forms
- The release of dissolved or colloidal radionuclides through the degraded engineered barriers to the host rock
- The transport of dissolved or colloidal radionuclides through the unsaturated zone to the water table
- The transport of dissolved or colloidal radionuclides through the saturated zone to the accessible environment
- The transport of radionuclides in the biosphere through a range of possible biological pathways to the point where they are either ingested or inhaled by humans.

Section 4.2 presents the models of each of these processes used as a basis for the TSPA model. *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a) assesses transport of radionuclides to the accessible environment consistent with 10 CFR Part 197.

4.4.2.2 Nominal Performance Results for Individual Protection Performance Measure

Information in this section is taken from *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a), *FY01 Supplemental Science and Performance Analyses* (BSC 2001a; BSC 2001b), *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a), and *Total System Performance Assessment Sensitivity Analyses for Final Nuclear Regulatory Commission Regulations* (Williams 2001b). Figure 4-179 illustrates the TSPA results for the nominal scenario. The time period of interest consistent with relevant NRC and EPA regulations is 10,000 years after the closure of the repository.[1] Nevertheless, this figure illustrates the dose that is projected to occur out to 100,000 years to gain insight. Because of the large uncertainty in applying the models to 100,000-year time frames, these projections should not be interpreted as predictions of probable future performance. They

[1] To complement the results of the 10,000-year performance assessment and consistent with EPA and NRC regulations at 40 CFR 197.35 and 10 CFR 63.341 (66 FR 55732) respectively, the peak dose to the reasonably maximally exposed individual beyond the 10,000-year time period has been calculated and included in the EIS as an indicator of long-term performance.

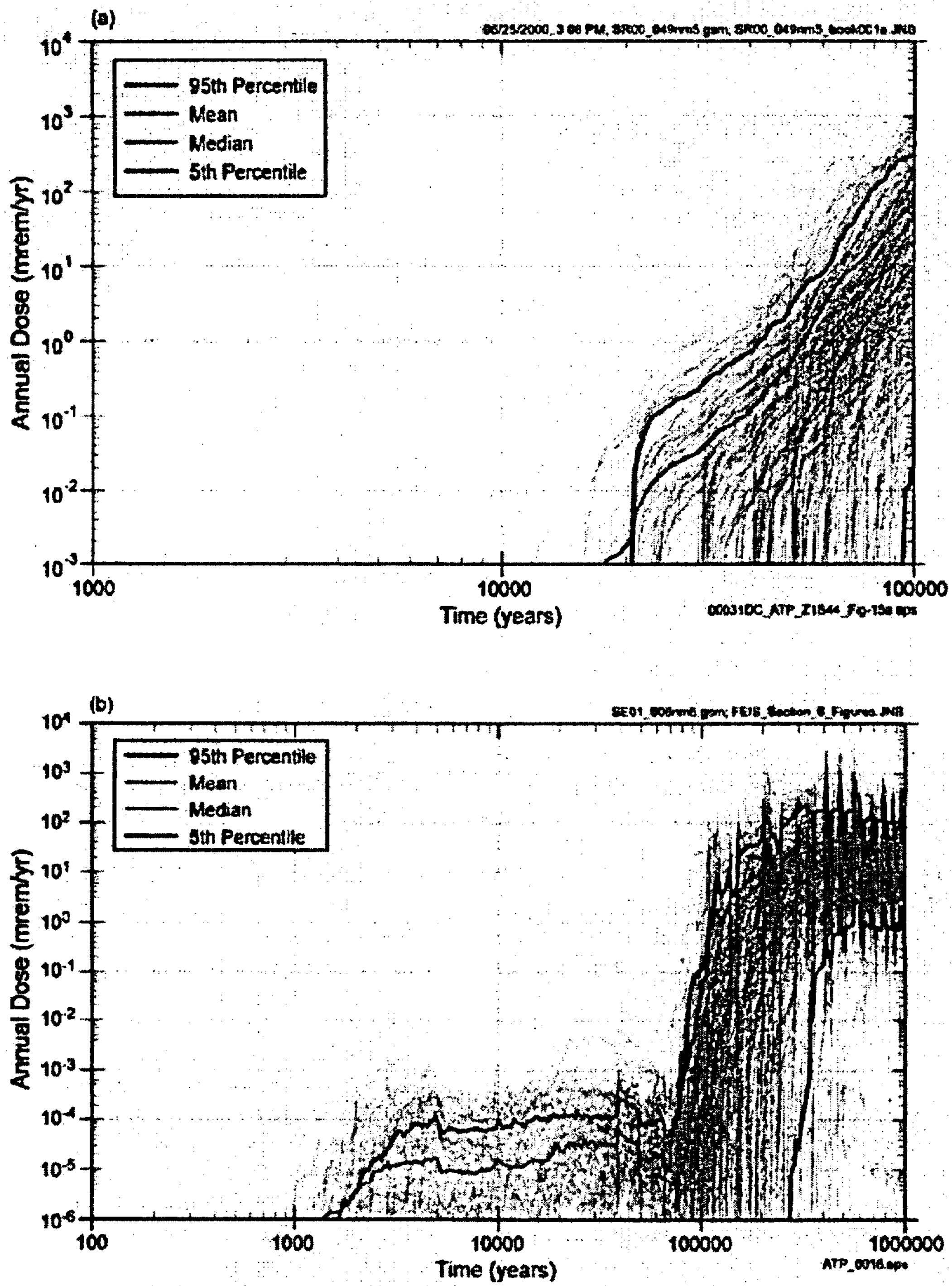


Figure 4-179. TSPA-SR Model and Revised Supplemental TSPA Model Results of Annual Dose to a Receptor for the Nominal Scenario

(a) Annual dose projected by the TSPA-SR model. (b) Annual dose projected by the revised supplemental TSPA model. The figures display the results for each simulation plotted, as well as the 5th and 95th percentiles, and the mean and median of these simulations to better examine the effects of uncertainty on the projected dose. Source: Modified from CRWMS M&O 2000a, Figure 4.1-5; Williams 2001a, Figure 6-5.

are simply indicators of the possible range of performance.

Figure 4-179 illustrates several statistical measures of how the repository system is likely to evolve and the projected dose rates associated with that probable evolution. The uncertainty in the overall projected performance is indicated by the wide range of possible outcomes. Each of the thin lines (also known as "horsetails") represents a single realization of the possible future performance of the repository system. The wide spread in the predicted outcomes is a direct result of the uncertainty in the component models summarized in Section 4.4.2.1 and described in detail in the subparts of Section 4.2. In addition to the complete distribution of results (represented by 300 distinct realizations), summary statistics indicating the 95th, 50th (or median), and 5th percentiles of the dose rate and the mean (or "expected") dose rate are also illustrated. These later statistical representations allow for an examination of the central tendency of the results.

As projected by the TSPA-SR model, no dose occurs for any of the 300 realizations for the nominal scenario of processes until more than 10,000 years after closure (Figure 4-179a). At 40,000 years, there is about a 5 percent probability of the dose rate being on the order of 1 mrem/yr or higher. At 60,000 years, there is about a 50 percent probability of the predicted dose being less than 1 mrem/yr. At 100,000 years, there is about a 50 percent probability of the predicted dose being on the order of 10 mrem/yr.

Based on updated information developed after completion of the TSPA-SR model, supplemental analyses were conducted to provide the basis for a modification of the TSPA-SR model. The results of these analyses are described in Volume 2, Section 3.2 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b) and in Section 4.4.5 of this report. Based on these sensitivity analyses, 20 component models were updated for the nominal scenario and one component model (igneous activity) was updated for the disruptive scenario to form the supplemental TSPA model (BSC 2001b, Sections 2.3 and 4.1). The peak mean dose projected by the supplemental TSPA model during the first 10,000 years is 2.0×10^{-4} mrem/yr for the higher-temperature operating mode and 6.0×10^{-5} mrem/yr for the lower-temperature operating mode, as presented in Volume 2, Section 4.1.1 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b). The supplemental TSPA analyses (Figure 4-180) and revised supplemental TSPA analyses (Figure 4-179b) include nonmechanistic early waste package failures that result in doses to the reasonably maximally exposed individual during the first 10,000 years. Doses after 10,000 years projected by the supplemental and revised supplemental TSPA models are lower than the results of the TSPA-SR model for the same time period (see Figure 4-180). The doses calculated for the nominal scenario by the supplemental TSPA model would be reduced by approximately one-third using an annual water demand of 3,000 acre-ft, consistent with NRC licensing regulations (see 10 CFR 63.312) (Williams 2001b, Section 6.3).

The waste package degradation model was further evaluated in *FY01 Supplemental Science and Performance Analyses* (BSC 2001a; BSC 2001b), and these changes were incorporated into the revised supplemental TSPA model used to project peak mean annual dose to the reasonably maximally exposed individual consistent with the EPA rule at 40 CFR Part 197. The peak mean dose projected by the revised supplemental TSPA model over a 10,000-year period is 1.7×10^{-5} mrem/yr for the higher-temperature operating mode and 1.1×10^{-5} mrem/yr for the lower-temperature operating mode. These evaluations are presented in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Section 6 and Table 6-1). These calculated doses would be reduced by approximately one-third using an annual water demand of 3,000 acre-ft, consistent with NRC regulations at 10 CFR 63.312 (66 FR 55732) (Williams 2001b, Section 6.3).

The supplemental and revised supplemental TSPA models forecast doses before 10,000 years, whereas the TSPA-SR model forecasts no dose in the first 10,000 years. The primary reason for this

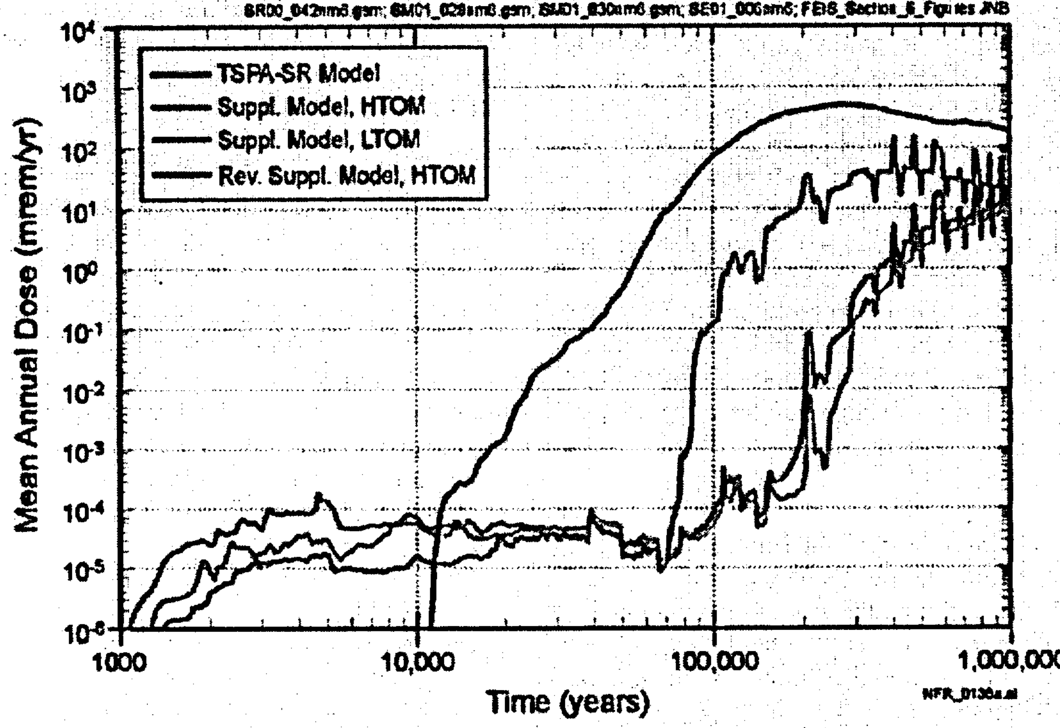


Figure 4-180. TSPA Model Results: Million-Year Annual Dose Histories for Nominal Performance

Mean annual dose histories are shown for the supplemental TSPA model for both higher-temperature and lower-temperature operating modes (HTOM and LTOM, respectively). These results are documented in Volume 2 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b). The nominal scenario results from the revised supplemental TSPA model for the higher-temperature operating mode, as documented in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a), are also shown. These calculated doses would be reduced by approximately one-third using an annual water demand of 3,000 acre-ft, consistent with NRC regulations. The effect of the 3,000 acre-ft annual water demand is discussed further in *Total System Performance Assessment Sensitivity Analyses for Final Nuclear Regulatory Commission Regulations* (Williams 2001b, Section 6.3). These revised supplemental TSPA model results are presented along with the nominal scenario TSPA-SR model results documented in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a). Source: Williams 2001a, Figure 6-14.

is the incorporation of nonmechanistic early waste package failures as described in the supplemental TSPA models (BSC 2001b, Section 4.1; Williams 2001a, Section 5.2.4.2). No mechanisms that could lead to early failure of waste packages were included in the TSPA-SR model. This was based on the low probability and the use of administrative controls to further reduce the probability of mechanisms that could lead to early failure. In reevaluating the potential of early failure mechanisms and their potential consequences, a more conservative approach resulted in the inclusion of improper heat treatment and subsequent possible failure of up to three waste packages in the supplemental TSPA analyses. The early waste package failure assumes failure of both the inner and outer Alloy 22 lids and the stainless steel inner lid. To ensure that the potential consequence of early waste package failures is treated conservatively, it was included in the nominal scenario, not as a sensitivity analysis, for the supplemental and revised supplemental TSPA model analyses. In the revised supplemental model, assuming nonmechanistic early failure of all waste packages would result in an annual dose during the first 10,000 years of less than 1 mrem/yr, or less than one-third of one percent of the average dose from natural background radiation.

The use of administrative (procedural) controls, engineering controls, and multiple checks included as part of the development of the induction annealing process, will reduce the probability of failures due to improper heat treatment. The inclusion of early failures has built conservatism into the nominal scenario simulated by both supplemental TSPA models. For the nominal scenario, these early failures are the only contributor to the early dose that begins at approximately 2,000 years and extends out to approximately 80,000 years in the supplemental and revised supplemental TSPA model evaluations of nominal performance (BSC 2001b, Section 5.1; Williams 2001a, Section 5.2.4.2).

The difference in projected dose between the TSPA-SR model and both supplemental TSPA models for the nominal case after 10,000 years resulted from an effort to quantify uncertainties and address conservatism found in the TSPA-SR model (Figure 4-180). The drop in peak annual dose for the supplemental and revised supplemental TSPA models after 10,000 years as compared to the TSPA-SR model is largely due to the more realistic treatment of radionuclide solubilities, particularly neptunium, thorium, and plutonium (BSC 2001b, Section 4.1). The increase in peak annual dose after 10,000 years from the supplemental TSPA model compared to the revised supplemental TSPA model is primarily due to the exclusion of the consideration of temperature dependence in Alloy-22 corrosion rates. The revised supplemental TSPA model used biosphere dose conversion factors based on the reasonably maximally exposed individual, whereas the TSPA-SR and supplemental TSPA model used biosphere dose conversion factors based on the average member of the critical group. Reasonably maximally exposed individual biosphere dose conversion factors are lower than those for the average member of the critical group. As a result, doses projected by the revised supplemental TSPA model were lower (Williams 2001a, Section 5.2.5) for the first 10,000 years. Calculated values of dose for the nominal scenario would be reduced by approximately one-third using an annual water demand of 3,000 acre-ft consistent with NRC regulations at 10 CFR 63.312. The effects of the change in annual water demand in the final NRC rule are discussed further in *Total System Performance Assessment Sensitivity Analyses for Final Nuclear Regulatory Commission Regulations* (Williams 2001b, Section 6.3).

Figures 4-181 and 4-182 illustrate the distribution of key radionuclides projected by the TSPA-SR model that contribute to the mean dose response depicted on Figure 4-179a. These figures indicate that for the first 50,000 years, the doses are dominated by the mobile, high solubility and poorly sorbing radionuclides, such as iodine-129 and technetium-99. After about 50,000 years, the doses are dominated by less mobile, lower solubility, and more sorbing radionuclides, such as neptunium-237 and both colloidal and dissolved plutonium-239.

The preceding figures describe the total system results in terms of the total annual dose to the receptor and the uncertainty in these results. However, it is also important to understand the causal relationships that determine these results. The following discussion describes the evolution of the potential repository as it relates to the performance of the overall system.

Before liquid water can contact the waste packages, the titanium drip shield must be breached. The drip shields are projected by the TSPA-SR model to remain intact for about 20,000 years; however, about half of the drip shields are projected to be breached after about 30,000 years.

The range of initial drip shield breach generally occurs between about 20,000 and 40,000 years, although there is a low probability that some drip shields remain intact for the entire 100,000-year simulation period. While the drip shields are intact, there is no liquid water which contacts the waste package; therefore, there is no possibility for advective releases from the waste package during this time period, even if a waste package were to degrade. The supplemental TSPA model projects drip shield lifetimes of 30,000 to 120,000 years (BSC 2001a, Section 7.4; BSC 2001b, Section 3.2.6.3).

The doses in the nominal scenario are delayed until after the waste packages are breached. In the

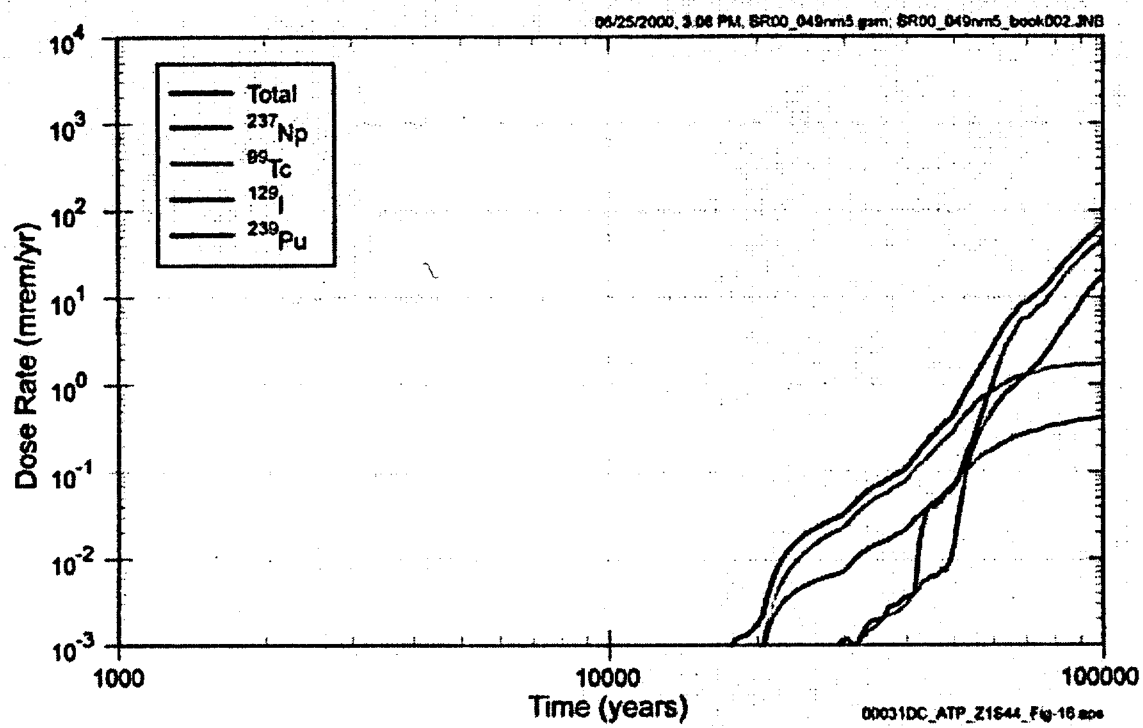


Figure 4-181. Mean Annual Dose Rate for Key Radionuclides for the Nominal Scenario Projected by the TSPA-SR Model

Source: Modified from CRWMS M&O 2000a, Figure 4.1-5.

TSPA-SR model, there is a 95 percent probability that the waste packages will remain intact until about 20,000 years, and there is a 50 percent probability that the waste packages will remain intact until about 40,000 years. However, there is a very small probability that the waste packages will begin to breach at about 11,000 years. The fact that the mean waste package failures occur prior to the 95th percentile failure distribution is indicative that there is a small probability (but less than five percent) that some waste packages will be degraded prior to 20,000 years. The supplemental TSPA model projects up to three waste package failures before 10,000 years due to nonmechanistic improper heat treatment of welds (BSC 2001a, Section 7.3.6).

Additional analyses of corrosion and waste package performance are described in *FY01 Supplemental Science and Performance Analyses* (BSC 2001a; BSC 2001b) and *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a).

The analyses assume that once the outer corrosion-resistant barrier (Alloy 22) of the waste package has degraded, moisture can enter the package. These analyses conservatively assumed that no time delay is attributed to the containment and isolation potentially afforded to the inner, less corrosion-resistant barrier of the waste package (stainless steel). In addition, no credit is taken for the pour canisters that encapsulate the high-level waste glass. Therefore, with the exception of the corrosion-resistant Zircaloy cladding that surrounds about 99 percent of the commercial spent nuclear fuel, once the waste package is breached by a crack penetrating the waste package, the waste form is exposed to moisture.

Once the waste form is exposed, it will begin to degrade and radionuclides will be released to the aqueous phase (whether liquid water or a thin film of moisture) in contact with the waste form. The rate of release to this aqueous phase is a function of

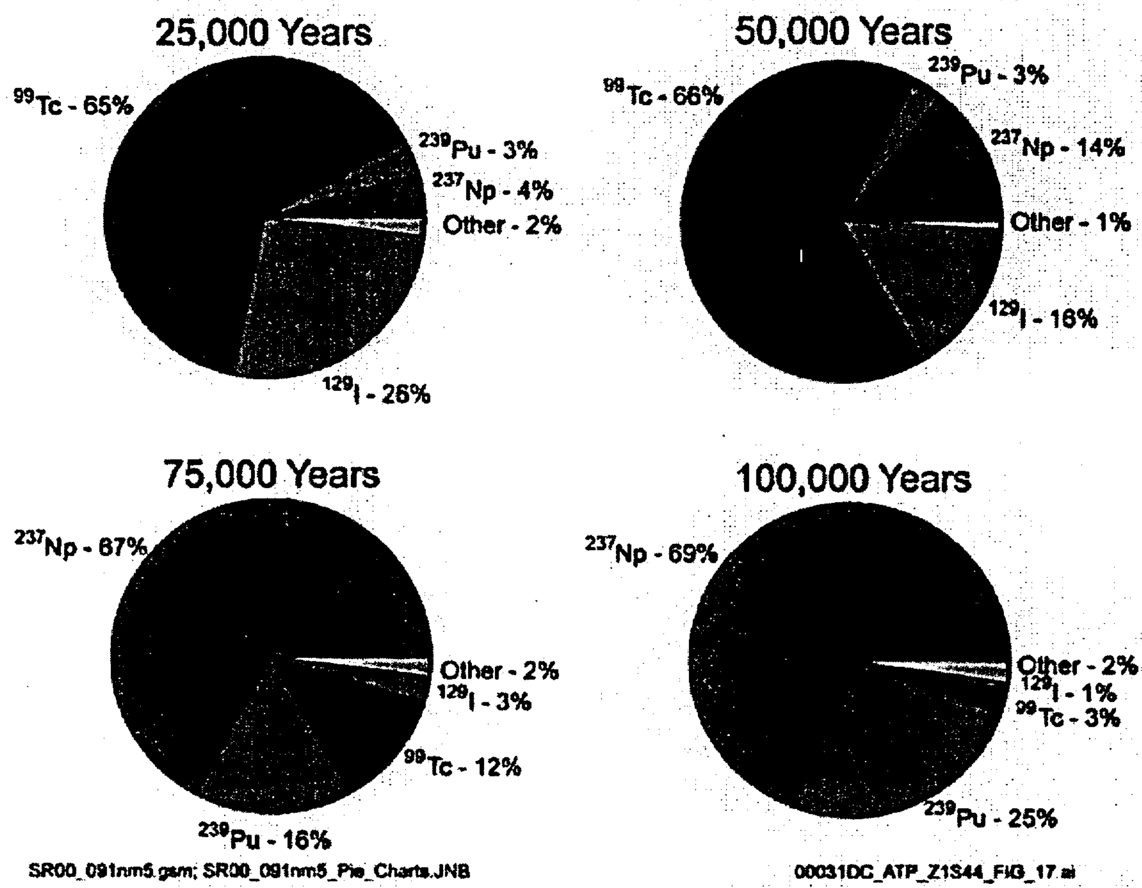


Figure 4-182. Fraction of Mean Total Annual Dose Attributed to Different Radionuclides for the Nominal Scenario Projected by the TSPA-SR Model

Times depicted are (a) 25,000 years, (b) 50,000 years, (c) 75,000 years, and (d) 100,000 years after closure. More mobile radionuclides, such as iodine-129 and technetium-99, dominate the dose at times less than 40,000 years, while neptunium-237 dominates the dose at longer times. Source: Modified from CRWMS M&O 2000a, Figure 4.1-6.

the rate of exposure of the waste, which includes the rate of waste package degradation and the rate of cladding degradation, as well as the rate of waste form degradation. In addition, the release rate is dependent on the solubility of the radionuclide in the moisture film that surrounds the exposed waste form. Once radionuclides are released from the waste form into the aqueous phase, they may be transported by advection (i.e., within flowing water) or diffusion (i.e., by concentration gradients through a continuous water film) through the waste package. Mobile radionuclides—those that are highly soluble or attached to mobile colloids—are transported through the degraded waste package and the invert material beneath the waste package to the host rock. The rate of release to the host rock depends on the mobility of the radionuclide and the amount of water available for transport.

Plutonium-239 is a low solubility, highly sorbed radionuclide that is generally immobile in aqueous environments. However, in the presence of colloidal material, plutonium-239 can sorb onto the colloid particles and be transported in the aqueous phase with the colloids. Two different types of colloids have been considered in TSPA: reversible colloids (where the radionuclide can sorb and desorb from the colloid) and irreversible colloids (where the radionuclide can not desorb from the colloid).

Mean radionuclide release rates from five locations for key radionuclides were assessed in the

TSPA-SR for the nominal scenario. These correspond to the following boundaries: (1) the edge of the waste form; (2) the edge of the waste package; (3) the edge of the engineered barrier system, which corresponds to the base of the drift invert; (4) the base of the unsaturated zone, which corresponds to the top of the water table; and (5) 20 km (12 mi) from the repository footprint. *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a) describes a nominal scenario TSPA with the controlled area extended approximately 18 km (11 mi) south from the repository footprint, consistent with 40 CFR 197.12 and 10 CFR 63.302 (66 FR 55732).

The analyses reveal several important insights into repository system behavior:

1. The initial mean rate of release of these radionuclides from the waste form is dependent on the mean time for initial degradation of the waste package. As soon as the packages are degraded, some mobile radionuclides may be released to the aqueous phase. The mean rate of release can precede the mean time to failure because the mean release rate is dependent on some very low probability early waste package failures. For example, there is a 1 percent chance of having at least one waste package failure at about 11,000 years, projected by the TSPA-SR model.

   The supplemental TSPA model results found in Volume 2, Section 3.2.5.4 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b, Figure 3.2.5.4-1) and the revised supplemental TSPA model results found in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Section 6.2.1, Figures 6-4 and 6-6) describe a nominal scenario in which doses from nonmechanistic early waste package failures occur as early as 1,000 years after closure.

2. The release rate from the waste form to the aqueous phase is significantly greater than the mean release rate from the waste package. This is a result of the fact that even though the waste package has failed (in that it no longer provides complete containment of the inventory), the initial failure is by very small stress corrosion cracks at the closure welds. These small cracks are sufficiently small to significantly reduce any diffusive (prior to drip shield degradation) or advective (after drip shield degradation) transport through them. Once a significant fraction of the waste package has been degraded, the release rate from the waste form and from the waste package become more equivalent.

3. In most instances, the release rate from the engineered barrier system is similar to the release rate from the waste package. This is a function of the diffusive release rate through the invert materials, for the assumed diffusivity in the partially saturated invert materials, being greater than that through the small cracks in the waste package.

4. The residence time of radionuclides through the unsaturated zone is dependent on the radionuclide. For nonsorbing radionuclides such as technetium-99, the residence time is on the order of hundreds of years for the glacial transition climate state present at the time radionuclides are released from the engineered barrier system. For more sorbing radionuclides such as neptunium-237, the residence time is on the order of thousands of years for the glacial transition climate state.

5. The delay in radionuclides that are released at the base of the unsaturated zone from reaching the accessible environment is also dependent on the degree

of sorption of the radionuclides. Less sorbing radionuclides have a short residence time, while more highly sorbed radionuclides have a longer residence time.

4.4.2.3 Nominal Performance Results for Groundwater Protection

The results of the TSPA-SR groundwater protection performance analyses are illustrated in Figures 4-183 and 4-184 for the concentration and dose performance measures, respectively. Figure 4-183 illustrates the combined radium-226 and radium-228 concentrations in the representative volume of groundwater, as well as the gross alpha-activity concentration (including radium-226 but excluding radon and uranium). Figure 4-184 shows the dose associated with the beta and photon emitting radionuclides (iodine-129, technetium-99, and carbon-14). The critical organs for these three radionuclides are the thyroid (for iodine-129), the gastrointestinal tract (for technetium-99), and fat (for carbon-14).

The natural background concentrations are not shown in these figures. The measured natural gross alpha background is 0.4 pCi/L ± 0.7 pCi/L. The measured natural total radium background is 1.04 pCi/L. The calculated activity concentration of radium-226 and radium-228, with background included, is still less than 5 pCi/L. If the background gross alpha activity is included, the sum of TSPA-SR projected gross alpha activity concentration plus natural background approaches 15 pCi/L at 100,000 years (CRWMS M&O 2000a, Section 4.1.5).

Consistent with proposed 40 CFR 197.35 (64 FR 46976), the TSPA-SR and supplemental TSPA models considered the radionuclide activity concentration in the groundwater, where the water volume considered is that equivalent to a representative volume of 1,285 acre-ft/yr. Groundwater protection was analyzed at the receptor location above the highest concentration of radionuclide in the plume. The plume volume was equivalent to a volume that would yield 1,285 acre-ft of annual groundwater withdrawal. The radionuclide concentrations were calculated by dividing the annual release of radionuclides that pass the receptor location by the representative volume. The water has been measured to have 385 mg/L of total dissolved solids (CRWMS M&O 2000a, Section 4.1.5). For the purposes of the maximally exposed organ dose, these analyses also assumed that the water was consumed at a rate of 2 L (0.5 gal) per day and that the ICRP-2 dose conversion factors were used.

Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation (Williams 2001a) assumes a representative volume of 3,000 acre-ft/yr. and an accessible environment location consistent with 40 CFR 197.31. These assumptions are included in the revised supplemental TSPA model.

Over 10,000 years, the peak mean annual activity concentration calculated by the supplemental TSPA model for combined radium-226 and radium-228 is 7×10^{-11} pCi/L (not including background radiation) for the higher-temperature operating mode (BSC 2001b, Section 4.1.4). The combined radium concentration for the lower-temperature operating mode is less than 10^{-10} (BSC 2001b, Section 4.1) (not including background radiation). The calculated peak mean activity concentration for gross alpha-emitting radionuclides is 7×10^{-8} pCi/L (not including background radiation) for the higher-temperature operating mode (BSC 2001b, Section 4.1.4). Plots of the gross alpha concentration for the lower-temperature operating mode indicate the activity concentration is approximately 3×10^{-8} pCi/L (BSC 2001b, Section 4.1) (not including background radiation). The calculated maximum dose to any critical organ projected by the supplemental TSPA model is 5×10^{-5} mrem/yr for the higher-temperature operating mode and 2×10^{-5} mrem/yr for the lower-temperature operating mode (BSC 2001b, Section 4.1.4). Further discussion of radionuclide concentrations and critical organ doses calculated by the supplemental TSPA model are given in Volume 2, Sections 4.1.4 and 5.5 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b).

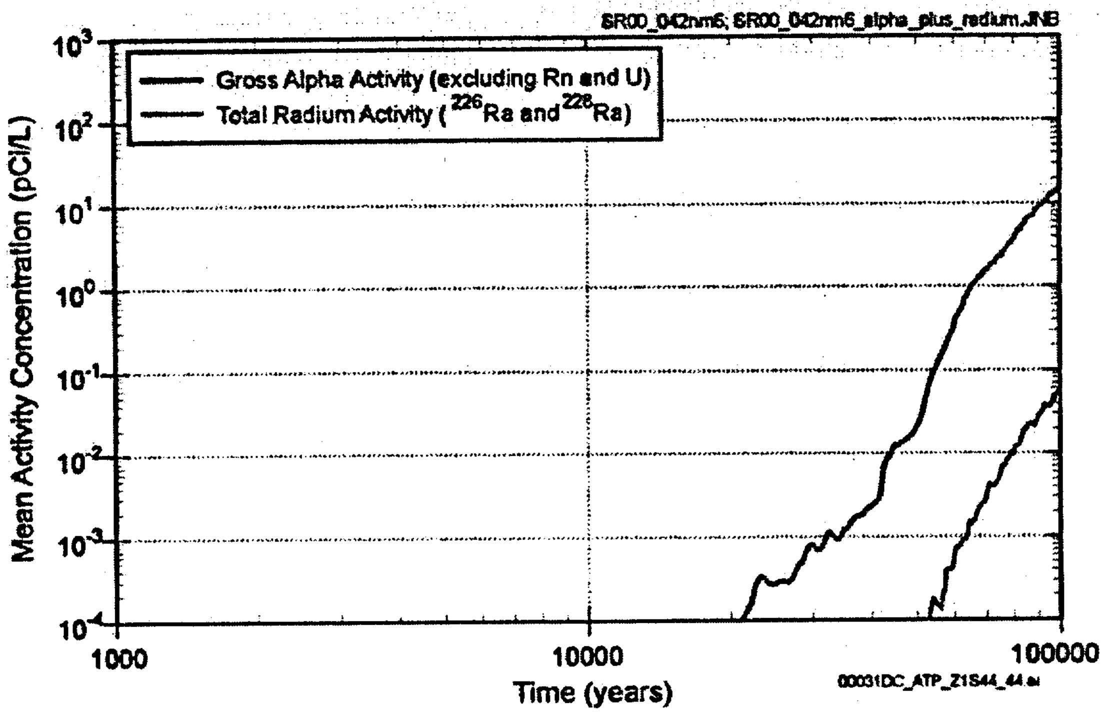


Figure 4-183. Mean Groundwater Concentrations for Gross Alpha and Total Radium Activity Projected by the TSPA-SR Model
Source: CRWMS M&O 2000a, Figure 4.1-24.

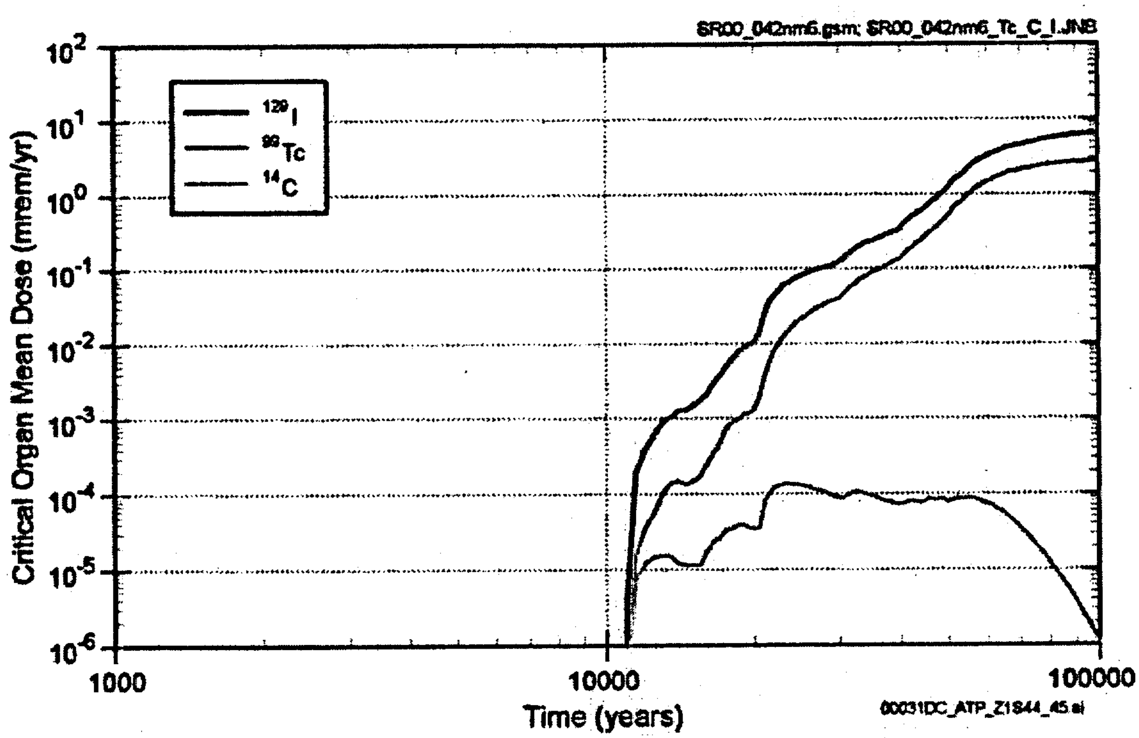


Figure 4-184. Mean Critical Organ Dose Rates Combined Beta- and Photon-Emitting Radionuclides Projected by the TSPA-SR model
Source: CRWMS M&O 2000a, Figure 4.1-27.

As shown in Figures 4-185 and 4-186, the peak mean annual activity concentration calculated by the revised supplemental TSPA model for combined radium-226 and radium-228 for the first 10,000 years is less than 10^{-10} pCi/L for both the higher-temperature and lower-temperature operating modes (not including background radiation) (Williams 2001a, Table 6-3). Figures 4-185 and 4-186 also show that the calculated peak mean activity concentration for gross alpha-emitting radionuclides for the first 10,000 years is 1.8×10^{-8} pCi/L (not including background radiation) for the higher-temperature operating mode and 3.3×10^{-8} pCi/L (not including background radiation) for the lower-temperature operating mode (Williams 2001a, Table 6-2).

As indicated, data taken from a Nevada Department of Transportation well approximately 20 km (12 mi) from the potential repository indicate that gross alpha background concentrations are 0.4 pCi/L ± 0.7 pCi/L; total radium background concentrations are no greater than 1.04 pCi/L (CRWMS M&O 2000a, Section 4.1.5). Because the calculated gross alpha and total radium concentrations are orders of magnitude lower than their natural background concentration, the combined background and calculated concentrations, when rounded, are the same as the natural background. The maximum mean dose to any critical organ projected by the revised supplemental TSPA model from combined beta- and photon-emitting radionuclides is 2.3×10^{-5} mrem/yr for the higher-temperature operating mode and 1.3×10^{-5} mrem/yr for the lower-temperature operating mode (Williams 2001b, Table 6-3). Radionuclide concentrations and critical organ doses calculated by the revised supplemental TSPA model are discussed in

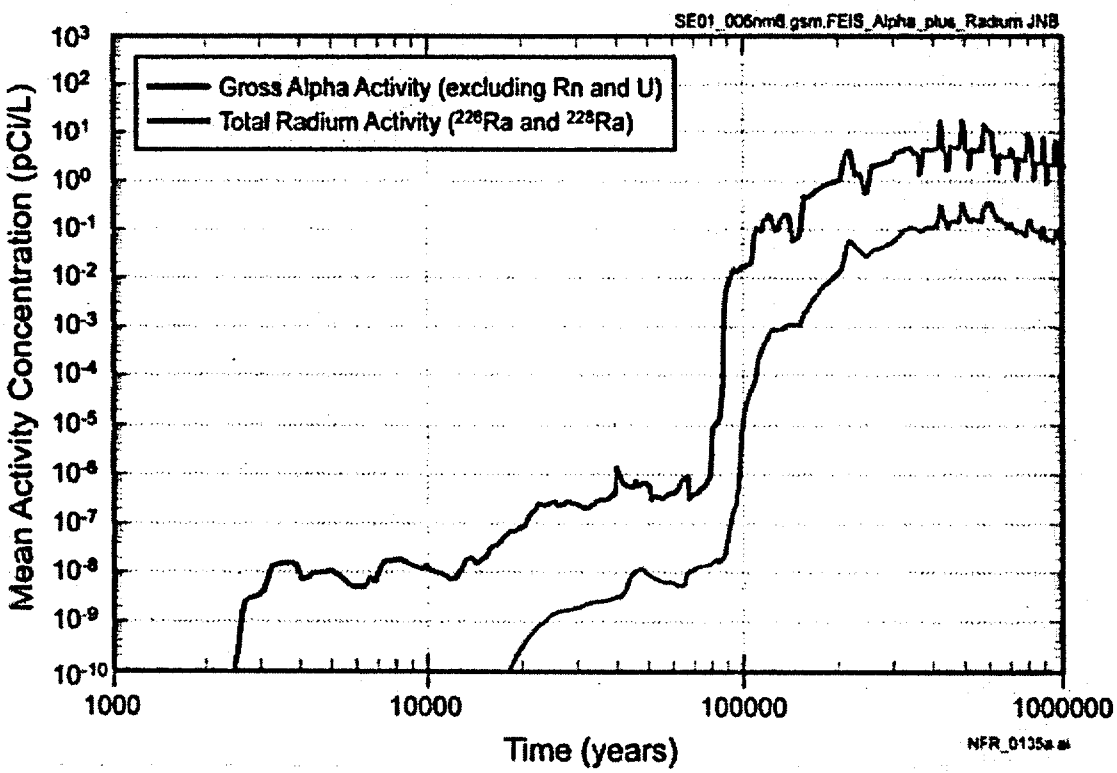


Figure 4-185. Mean Activity Concentrations of Gross Alpha Activity and Total Radium in the Groundwater, Higher-Temperature Operating Mode

Nominal scenario revised supplemental TSPA model results for 1 million years. Concentrations calculated for an annual representative volume of water of 3,000 acre-ft, approximately 18 km (11 mi) from within the potential repository footprint. Naturally occurring background radionuclide concentrations are not included. Source: Williams 2001a, Figure 6-17.

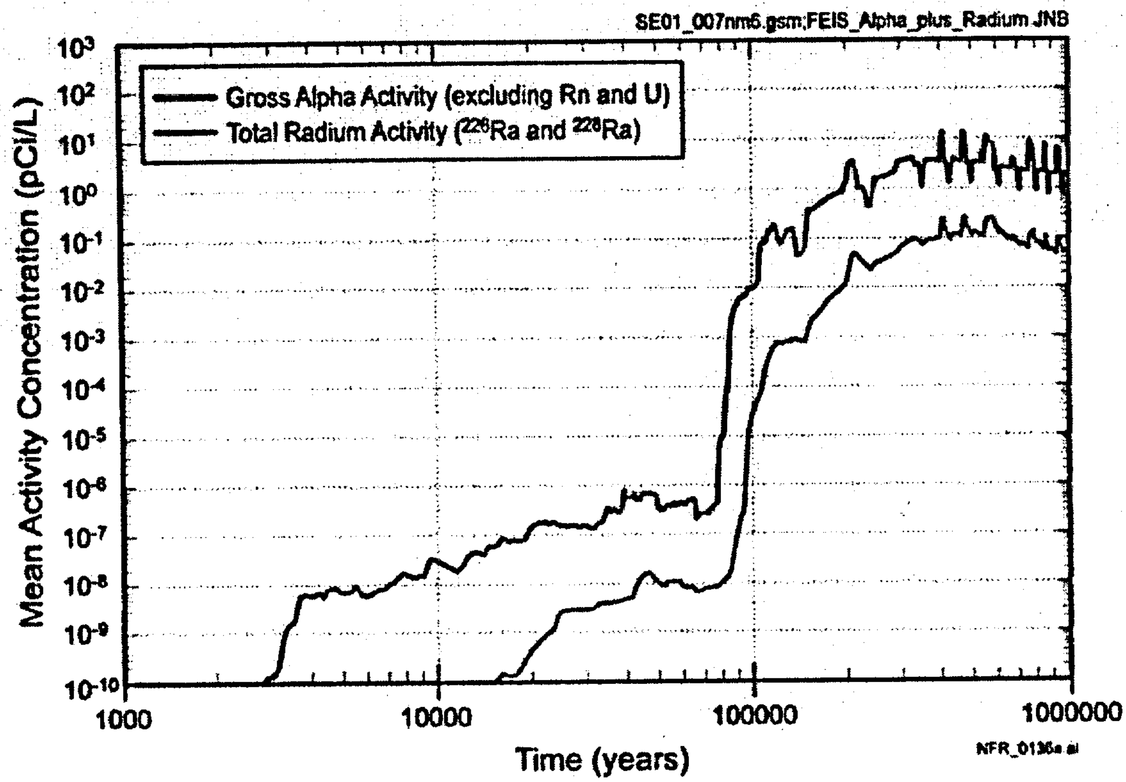


Figure 4-186. Mean Activity Concentrations of Gross Alpha Activity and Total Radium in the Groundwater, Lower-Temperature Operating Mode

Nominal scenario revised supplemental TSPA model results for 1 million years. Concentrations calculated for an annual representative volume of water of 3,000 acre-ft, approximately 18 km (11 mi) from within the potential repository footprint. Naturally occurring background radionuclide concentrations are not included. Source: Williams 2001a, Figure 6-18.

more detail in Section 6.6 of *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a).

The DOE conducted additional sensitivity analyses and documented these in *Total System Performance Assessment Sensitivity Analyses for Final Nuclear Regulatory Commission Regulations* (Williams 2001b). The report includes estimates of activity concentrations and dose estimates from combining releases from the nominal scenario with those from an unlikely event (igneous intrusion scenario) for the evaluation of groundwater protection. Because the nominal scenario results are negligible compared to the results calculated for an unlikely igneous intrusion, the activity concentrations and dose estimates for groundwater protection considering igneous intrusion are approximated as those calculated for an igneous intrusion. Gross alpha concentration for the igneous intrusion scenario was calculated as 2.9×10^{-2} pCi/L for the higher-temperature operating mode and 5.5×10^{-2} pCi/L for the lower-temperature operating mode. These concentrations are about 10 percent of natural background radiation. Total radium concentration was 5×10^{-6} pCi/L for the higher-temperature operating mode and 5.2×10^{-6} pCi/L for the lower-temperature operating mode. These concentrations are orders of magnitude lower than natural radiation. The calculated maximum dose to any critical organ for the igneous intrusion scenario was 2.5×10^{-1} mrem/yr for the higher-temperature operating mode and 2.4×10^{-1} mrem/yr for the lower-temperature operating mode (Williams 2001b, Tables 6-1, 6-2, and 6-3).

4.4.2.4 Nominal Performance Results for Peak Dose

Consistent with both EPA and NRC rules (40 CFR 197.35 and 10 CFR 63.341 [66 FR 55732] respectively), the DOE has evaluated the peak dose to the reasonably maximally exposed individual during the period of geologic stability and has included these results in the EIS. The National Academy of Science has estimated the period of geologic stability at Yucca Mountain to be on the order of 1 million years (National Research Council 1995, pp. 71 and 72). There are several important limitations that should be emphasized in interpreting the results of the million-year calculations.

The models developed for use in the nominal performance assessment have focused on the first 10,000 years, consistent with EPA and NRC regulations. As a result, these models have not considered longer term processes such as long-term climate change in their development. For example, the climate change considered in the nominal performance analyses for the TSPA-SR model is limited to changes over the next 10,000 years and has neglected the possible changes during full glacial time periods. As a result, the climate model had to be modified to include glacial time periods to perform peak dose analyses.

The post-10,000-year analyses are designed to provide additional confidence that public health and safety will be protected. Extending nominal performance results beyond 10,000 years provides a reasonably conservative representation of the peak dose.

The main reason for estimating peak doses is to provide the DOE, regulators, and the public with additional information about long-term repository performance. It is important to note that the component models in the TSPA-SR model are believed to be relatively conservative for the 10,000-year time period and may be highly conservative when applied to time periods on the order of 100,000 or 1 million years. One of these conservative models is the retention of moderate and low-solubility radionuclides, such as neptunium-237 and plutonium-239, in the secondary phases of uranium that are formed as the spent fuel waste forms are altered. Models of secondary phase (CRWMS M&O 2000dr) on radionuclide solubility have been developed based on data from long-term drip tests conducted at Argonne National Laboratory (CRWMS M&O 2000dk).

Analyses in Volume 2 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b) had as one of their primary goals to quantify previously unquantified uncertainties. This was done primarily to aid in understanding the degree of conservatism in the calculation.

A second goal of this evaluation was to assess the impact of the conservatisms on the peak dose calculation. For example, not taking secondary phase effects into account simplifies the modeling process, but it makes the peak dose estimate highly pessimistic. In contrast, assuming the climate state at 10,000 years stays the same for the next 990,000 years probably makes the peak dose calculation optimistic. Both processes must be accounted for to make the peak dose calculation. These two processes in particular may represent the most significant potential sources of optimism and pessimism in the TSPA-SR model peak dose. As other optimistic or pessimistic simplifications were identified, however, sensitivity studies have been done to evaluate their importance to the peak dose determination.

The results of the TSPA-SR model mean peak dose performance assessments assuming the models developed for the 10,000-year time period and extrapolated to 1 million years (CRWMS M&O 2000a, Section 4.1.3) are illustrated in Figure 4-187. This plot essentially continues the trends illustrated on the 100,000-year nominal performance analyses illustrated in Figure 4-179. The mean peak dose to the receptor for this plot is about 460 mrem/yr and occurs at about 270,000 years.

The results of the TSPA-SR model mean peak dose performance assessments using a preliminary secondary-phase solubility model (CRWMS M&O 2000a, Section 4.1.3) are illustrated in Figure 4-188. The mean peak dose to the receptor for this plot is about 30 mrem/yr and occurs much later (i.e., 500,000 to 600,000 years).

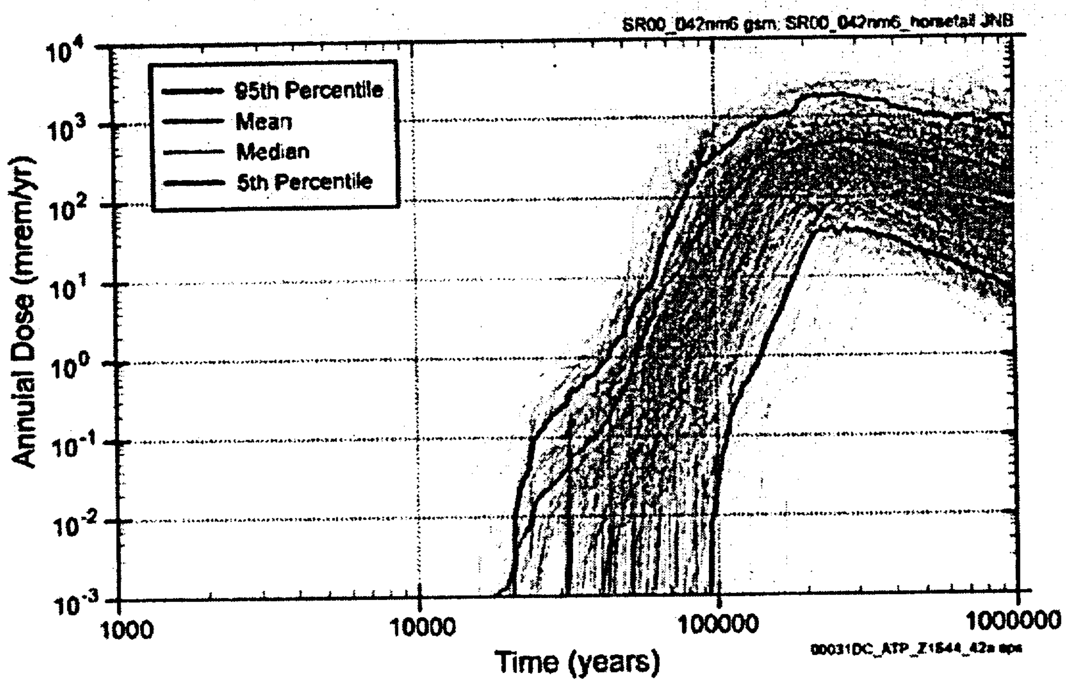


Figure 4-187. TSPA-SR Model Results for the Million-Year Annual Dose to a Receptor for the Nominal Scenario Using Nominal TSPA Models

The figure displays the results for each simulation as well as the 5th and 95th percentiles, and the mean and median of these simulations to better examine the effects of uncertainty on the projected dose. Source: CRWMS M&O 2000a, Figure 4.1-19a.

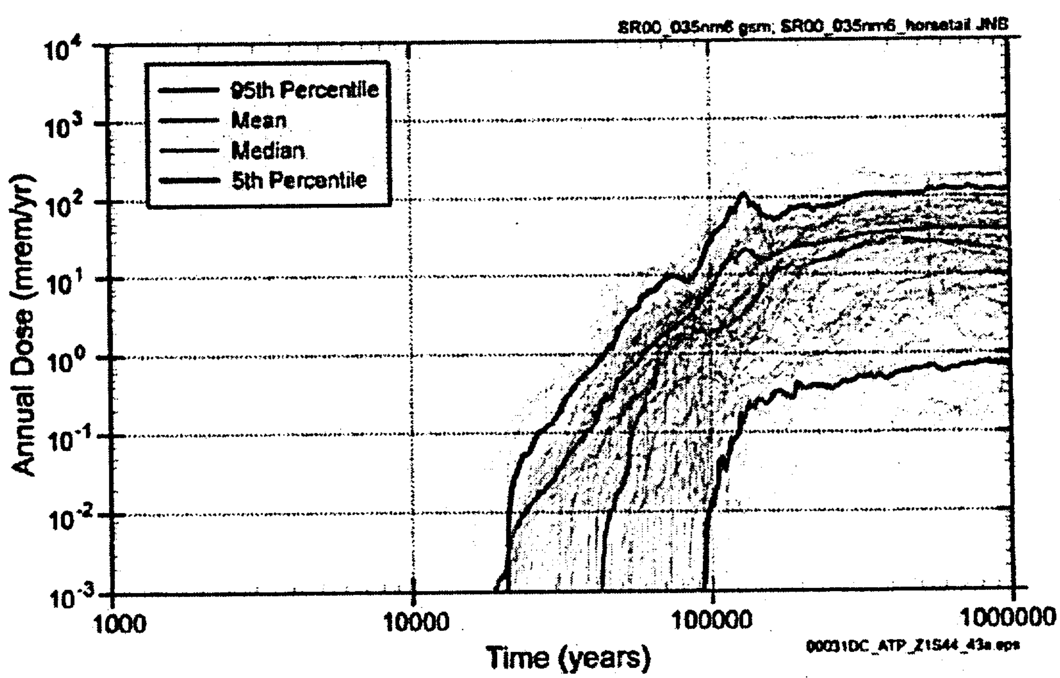


Figure 4-188. TSPA-SR Model Results for the Million-Year Annual Dose to a Receptor for the Nominal Scenario Using Nominal TSPA-SR Models and Revised Solubility Model

The figure displays the results for each simulation, as well as the 5th and 95th percentile, and the mean and median of these simulations to better determine the effects of uncertainty on the projected doses. Source: Modified from CRWMS M&O 2000a, Figure 4.1-21 (all realizations included).

The results of the TSPA-SR model mean peak dose performance assessments using a more representative long-term climate model and the revised secondary-phase solubility model (CRWMS M&O 2000a, Section 4.1.3) are illustrated in Figure 4-189. The peak dose to the receptor for this plot is about 100 mrem/yr. This current estimate for the peak dose value is about a third of the average annual background dose currently experienced in Amargosa Valley (DOE 1999a, Table 3-28).

The revised supplemental TSPA model calculations of peak mean annual dose to the reasonably maximally exposed individual after 10,000 years can be found in Section 6 of *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a). As shown in Figure 4-190, the peak mean annual dose over the first 100,000 years after closure for the nominal scenario is 1.2×10^{-1} mrem/yr for the higher-temperature operating mode and 8.5×10^{-2} mrem/yr for the lower-temperature operating mode (Williams 2001a, Table 6-1). The peak mean annual dose over the first million years after closure for the nominal scenario is 152 mrem/yr for the higher-temperature operating mode and 122 mrem/yr for the lower-temperature operating mode (Williams 2001a, Figure 6-3 and Table 6-1). Note that calculated doses for the nominal scenario would be reduced by approximately one-third using an annual water demand of 3,000 acre-ft, consistent with NRC regulations (Williams 2001b, Section 6.3). The DOE also included the results of this analysis (peak dose after 10,000 years) in the final EIS.

4.4.2.5 Summary of Nominal Scenario Performance Assessment Results

This section has described three measures (individual protection, groundwater protection, and peak dose) for evaluating the performance of the Yucca Mountain repository system. These analyses have been conducted to 100,000 years to evaluate

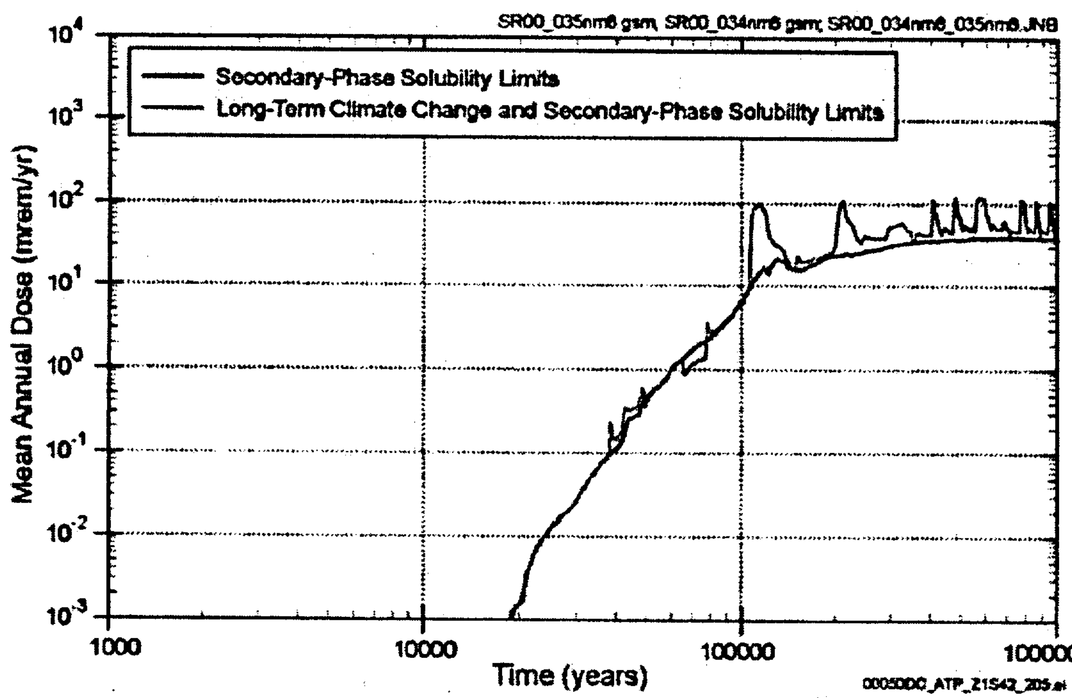


Figure 4-189. TSPA-SR Model Results for Million-Year Annual Dose to a Receptor for the Nominal Scenario Using Nominal TSPA-SR Models and Revised Solubility and Climate Models
Source: Modified from CRWMS M&O 2000a, Figure 4.1-21.

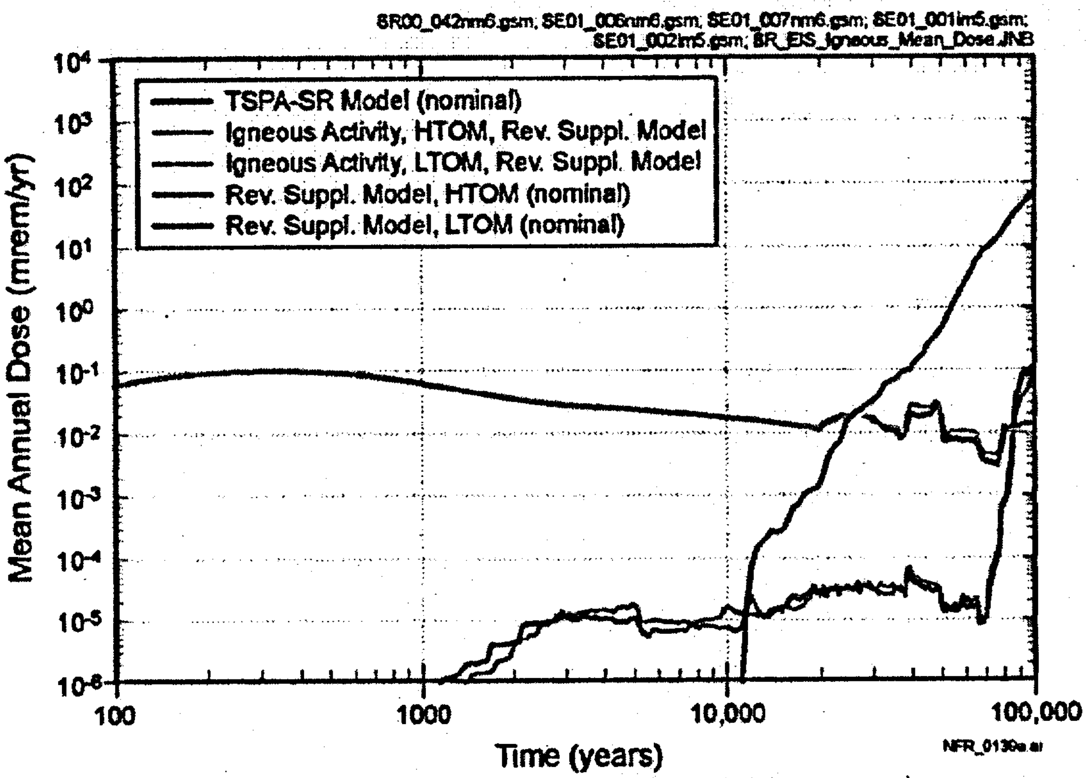


Figure 4-190. 100,000-Year Annual Dose Histories: TSPA-SR Model and Revised Supplemental TSPA Model (Nominal Scenarios) and Revised Supplemental TSPA Model (Igneous Activity)

Mean annual dose histories are shown for the TSPA-SR model and the revised supplemental TSPA model for the nominal scenarios, along with the probability-weighted mean annual dose history for the igneous activity disruptive scenario for the revised supplemental TSPA model for both the higher-temperature operating mode (HTOM) and the lower-temperature operating mode (LTOM). The results from the TSPA-SR model are documented in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000b). The results from the revised supplemental TSPA model are documented in the *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a). Source: Williams 2001a, Figure 6-16.

the robustness of the repository performance beyond 10,000 years. In addition, peak dose analyses required in the EIS have also been presented in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a). The peak mean annual dose calculated by the revised supplemental TSPA model for 100,000 years after closure is 1.2×10^{-1} mrem/yr for the higher-temperature operating mode and 8.5×10^{-2} mrem/yr for the lower-temperature operating mode (Williams 2001a, Table 6-1). The peak mean annual dose over 1 million years calculated by the revised supplemental TSPA model is 152 mrem/yr for the higher-temperature operating mode and occurs at 476,000 years. The peak mean annual dose for 1 million years for the lower-temperature operating mode is 122 mrem/yr and also occurs at 476,000 years. Calculated values of dose for the groundwater-pathway-dominated scenarios, such as the nominal scenario, would be reduced by approximately one-third using an annual water demand of 3,000 acre-ft, consistent with NRC regulations (Williams 2001b).

The next two sections, Sections 4.4.3 and 4.4.4, describe other analyses for assessing the performance of the repository system, namely, disruptive events scenario performance and human intrusion scenario performance. Section 4.4.5 provides a discussion of the sensitivity of the projected repository performance to the uncertainties in the component models described in Section 4.2.

4.4.3 Total System Performance for the Disruptive Scenario

As described in Section 4.4.1.3, volcanic activity has been identified as the only disruptive event that has the potential to affect disposal system performance during the first 10,000 years. Other disruptive FEPs, such as seismic perturbations of the water table and nuclear criticality, were analyzed and found either to be unsupported by scientific evidence or to have probabilities less than 1 in 10,000 in 10,000 years. As a result, these disruptive FEPs were not incorporated into the TSPA models through the formal FEPs screening procedure (BSC 2001t; CRWMS M&O 2000f, Table 2-2; see also Section 4.3 of this report). Potential seismic effects on the underground facilities and waste packages were screened out (i.e., excluded from consideration) because the waste packages would not be adversely damaged by design basis rockfalls or vibratory ground motion (CRWMS M&O 2000ex, Section 6.2). However, because vibratory ground motion from seismic events might damage the commercial spent nuclear fuel cladding, the effect of this potential damage to cladding by a discrete seismic event is included in the TSPA model in the nominal scenario. The frequency assumed for this event is 1.1×10^{-6} per year. For this analysis, when the vibratory ground motion event occurs, all commercial spent nuclear fuel cladding in the repository is assumed to fail by perforation, and further cladding degradation is calculated according to the cladding degradation.

The disruptive scenario considers two distinct types of volcanic activity: (1) eruptive volcanism at the repository location and (2) igneous intrusion (or magmatic flooding) of some of the emplacement drifts in the repository. *Disruptive Events Process Model Report* (CRWMS M&O 2000f) documents the geological basis and data for these scenario conceptualizations. The disruptive scenario assumed that the eruptive event consisted of a magmatic penetration of the repository facility after permanent closure. The conceptualization of the eruptive event assumes that the magma flow intersects and destroys waste packages, bringing waste to the surface through one or more eruptive conduits. The igneous intrusion event assumes that a hypothetical igneous dike intersects drifts of the repository and that the associated waste packages are damaged, exposing the waste within to percolating water. In the eruptive event, the TSPA models analyzed the atmospheric transport of radionuclides bound in the particles of volcanic ash that were then dispersed downwind and ultimately deposited on the ground at the receptor location. In the igneous intrusion event, the TSPA models accounted for the additional waste package failures and analyzed the transport of radionuclides through the groundwater pathway to the location of the receptor (average member of the critical group for the TSPA-SR and supplemental TSPA models and the reasonably maximally exposed individual for the revised supplemental TSPA model).

A probabilistic volcanic hazards assessment study (CRWMS M&O 1996b) focused on the task of examining available geologic data for the Yucca Mountain region and estimated the annual probability for the scenario of the repository footprint being intersected by a basaltic dike. A group of about 30 earth scientists from such organizations as the U.S. Geological Survey; the University of Nevada, Las Vegas; the Center for Nuclear Waste Regulatory Analyses; and Los Alamos National Laboratory contributed to this study. After this study, a formal elicitation of expert judgment was conducted in accordance with NRC guidance on elicitation procedures (Kotra et al. 1996). The expert panel used in the formal elicitation was composed of ten internationally recognized volcanism experts. The probability estimate obtained from the expert panel was 1.5×10^{-8} per year (or a probability of 1.5×10^{-4} of occurring over 10,000 years) (CRWMS M&O 1996b, Section 4.3). The probability estimate for the igneous intrusion event was subsequently recalculated based on a change in the configuration of the repository layout. The more recent probability estimate for the igneous intrusion event is 1.6×10^{-8} per year (CRWMS M&O 2000ez, Section 6.5.3.1). If a dike does intersect the repository, there is about a 77 percent chance that a volcano will form at the surface with magma flowing through a portion of the repository (the eruptive event) (CRWMS M&O 2000ez, Section 7.1.3 and Table 13a). This translates to approximately 1 chance in 7,700 of a volcano forming above the repository during the first 10,000 years. The annualized probabilities for each of the disruptive events are just slightly greater than the probability cutoff of 10^{-8} per year. Therefore, both intrusive and eruptive events have been included in the TSPA model analyses of the disruptive scenario.

The following sections briefly summarize the two models. More details on the results of the TSPA-SR model can be found in the *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a, Section 3.10.2). The results of the supplemental and revised supplemental TSPA models for the volcanic eruption and igneous intrusion models are summarized in Volume 2, Section 4.3 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b). *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a), and *Total System Performance Assessment Sensitivity Analyses for Final Nuclear Regulatory Commission Regulations* (Williams 2001b).

4.4.3.1 Total System Performance Assessment Model for Volcanic Eruption

The TSPA model for the consequences of a volcanic eruption at Yucca Mountain is a simplification of the complex processes that could occur during an eruption. At a conceptual level, the overall model is straightforward (Figure 4-191): an igneous dike rises through the earth's crust and intersects one or more drifts in the repository. An eruptive conduit forms somewhere along the dike as it nears the land surface, feeding a volcano at the surface. Waste packages in the direct path of the conduit are sufficiently damaged that they provide no further protection, and the waste is available to be entrained in the eruption. Volcanic ash is contaminated, erupted, and transported by wind toward the receptor. Ash settles out of the plume as it is transported downwind, resulting in an ash layer on the land surface. Receptors (the average

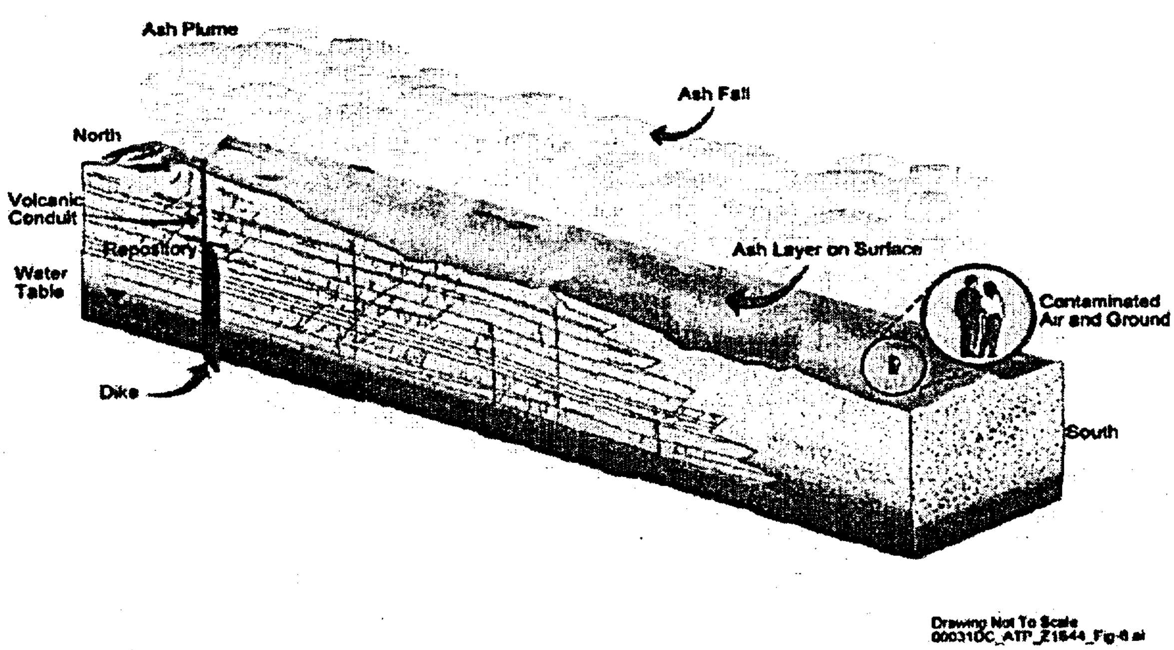


Figure 4-191. Schematic Representation of a Volcanic Eruption at Yucca Mountain, Showing Transport of Radioactive Waste in an Ash Plume

member of the critical group was the receptor used in the TSPA-SR model and supplemental TSPA models, while the reasonably maximally exposed individual was the receptor used in the revised supplemental TSPA model) could receive a radiation dose from various pathways associated with the contaminated ash layer.

This component model is implemented in the TSPA models through the selection of reasonable assumptions about many aspects of the event, the development of input parameter distributions characterizing important physical properties of the system, and the use of a computational model to calculate entrainment of the waste in the erupting ash and concentration of waste reaching the receptor.

Each intrusive event (i.e., a swarm of one or more dikes) is assumed to generate one or more volcanoes somewhere along its length, but eruptions need not occur within the repository footprint. In the TSPA-SR model (CRWMS M&O 2000a), approximately 36 percent of intrusive events that intersect the repository are associated with one or more (up to a maximum of five) eruptions within the footprint. Characteristics of the eruption, such as eruptive power, style (violent versus normal), velocity, duration, column height, and total volume of erupted material, are included in the analysis.

The number of waste packages damaged by an eruptive event is determined by the diameter of the eruptive conduit. Conduit diameter is a sampled parameter in the TSPA-SR calculation. Analogue sites were evaluated in *Characterize Eruptive Processes at Yucca Mountain, Nevada* (CRWMS M&O 2000fa, Section 6.1), and the distribution for conduit diameter was identified as log normal, with a minimum value equal to dike width, with a median value of 50 m (164 ft) and a maximum value of 150 m (490 ft). As a conservative assumption, *Number of Waste Packages Hit by Igneous Intrusion* (CRWMS M&O 2000fi) defined the minimum conduit diameter for the TSPA-SR calculation as 15 m (49 ft). For the purposes of the TSPA-SR model, the contents of all packages that are fully or partially damaged by an eruption (i.e., that lie partly or entirely within the circumference of the conduit) are assumed to be fully available for entrainment in the eruption. Waste packages, drip shields, cladding, and all other components of the engineered barrier system are assumed to be so damaged that they provide no further protection for the waste. This assumption provides a conservative bound to the possible behavior of the engineered barriers in the eruptive environment.

The physical properties of the waste in the eruptive environment are estimated based on the assumption that the waste form is directly exposed to the eruption, which is consistent with the assumption that the waste packages provide no protection.

The volcanic eruption and subsequent transport of radioactive material in the ash plume are modeled using a parametric characterization of the properties of the eruption to calculate a source term of ash for atmospheric transport. The quantity of ash deposited at any specified point is a function of the wind speed and direction, the volume of ash erupted (which determines the duration and height of the eruption), and the ash particle diameter. The ash particle diameter distribution used in the TSPA-SR model is based on observations from violent eruptions at modern analogue volcanoes and is defined as a log triangular distribution with a minimum value of 0.01 mm (0.00039 in.), a mode value of 0.1 mm (0.0039 in.), and a maximum value of 1 mm (0.039 in.) (CRWMS M&O 2000fa, Section 6.5.1). Waste particles are entrained in the eruption based on the ratio between their diameter and the diameter of the ash particles. In the TSPA-SR, it is assumed that waste particles one half the diameter of the ash or smaller are incorporated into the ash particles and transported downwind.

Projections of future wind conditions at Yucca Mountain are based on the speed and direction data sampled from distributions developed from past observations in the region. As with most weather data, short-term variability is relatively high, covering a broad range of uncertainty appropriate for the analysis of relatively brief volcanic events. Although speed and direction are reported as paired data for each observation at each elevation, the two parameters are sampled independently in the TSPA-SR model, allowing for a full coverage of wind speeds in each direction. Speeds range from 0 to approximately 2,000 cm/s (0 to 65.6 ft/s), with a median speed of approximately 650 cm/s (21.3 ft/s). Direction is variable, consistent with the observed data, but the decision to treat direction and speed as uncorrelated parameters allows flexibility in the TSPA to consider cases in which the wind direction is fixed toward a specific location in all realizations, rather than allowed to vary. For the TSPA-SR model, results are calculated assuming wind blows to the south in all realizations. This assumption is unrealistic but provides a conservative bound to uncertainty regarding wind direction and compensates for uncertainty regarding the possibility that contaminated ash deposited by winds blowing in directions other than south might later be redistributed to the location of the receptor.

More recent analyses of igneous activity can be found in Volume 2, Sections 4.3 and 5.2 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b), *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a), and *Total System Performance Assessment Sensitivity Analyses for Final Nuclear Regulatory Commission Regulations* (Williams 2001b). These analyses assessed the impact of higher wind speeds and larger waste particles. Using a median wind speed of 1,000 cm/sec (393.7 in./sec), the probability-weighted annual doses for the supplemental TSPA model were increased by a factor of 2. Performance is relatively insensitive to uncertainty in waste package diameter within the range considered in the supplemental TSPA model analysis (BSC 2001b, Section 3.3.1.2).

4.4.3.2 Total System Performance Assessment Model for Groundwater Transport of Radionuclides Following Igneous Intrusion

The TSPA models for radionuclide release and transport away from packages damaged by an igneous intrusion that intersects the repository is similar to the nominal model for radionuclide release and transport but modified to include the intrusion (Figure 4-192). Because flow and transport occur in the same units modeled for nominal performance, there is no separate set of computational models used in the TSPA to simulate the consequences of intrusion (CRWMS M&O 2000a, Section 3.10.2.3). Instead, the igneous intrusion groundwater transport model consists of a set of input parameters used to define a modified source term for calculations using the flow and transport models developed for the nominal case. There are three main components to the model: the behavior of waste packages and other elements of the engineered barrier system that have been damaged because of their nearness to an igneous intrusion; groundwater flow and radionuclide transport away from the waste packages; and calculation of the number of waste packages that are damaged.

The behavior of a waste package in the intrusive environment is bounded by the conservative assumption that packages close to the point of intrusion are so damaged that they provide no further protection for the waste. As in the case for the eruptive environment, actual conditions are uncertain, and damage is likely to range from moderate to extensive. Abstracted models for seepage, radionuclide mobilization, and transport are used in place of a separate set of detailed source term, flow, and transport models for the conditions in the drift following intrusion. Possible effects of uncertainty regarding conditions in the drift following intrusion are incorporated in the TSPA models through the assumption that all waste in the most severely damaged packages is immediately available for transport in the unsaturated zone, depending on solubility limits and the availability of water. The thermal, chemical, and mechanical effects of the intrusion that might tend to limit water seepage into the drift, at least temporarily, are neglected. No credit is taken for water diversion by pyroclastic debris, chilled lava, or the remnants of the drip shield or waste package, and cladding is assumed to be fully degraded.

For repository design alternatives that include backfill, damage within a drift is limited to the three packages on either side of the intrusion. Backfill pushed up by displaced waste packages and debris from damaged drip shields will stop magmatic material as it moves away from the dike, and the drift is assumed to be plugged relatively close to the intrusion. Pressure will increase in the

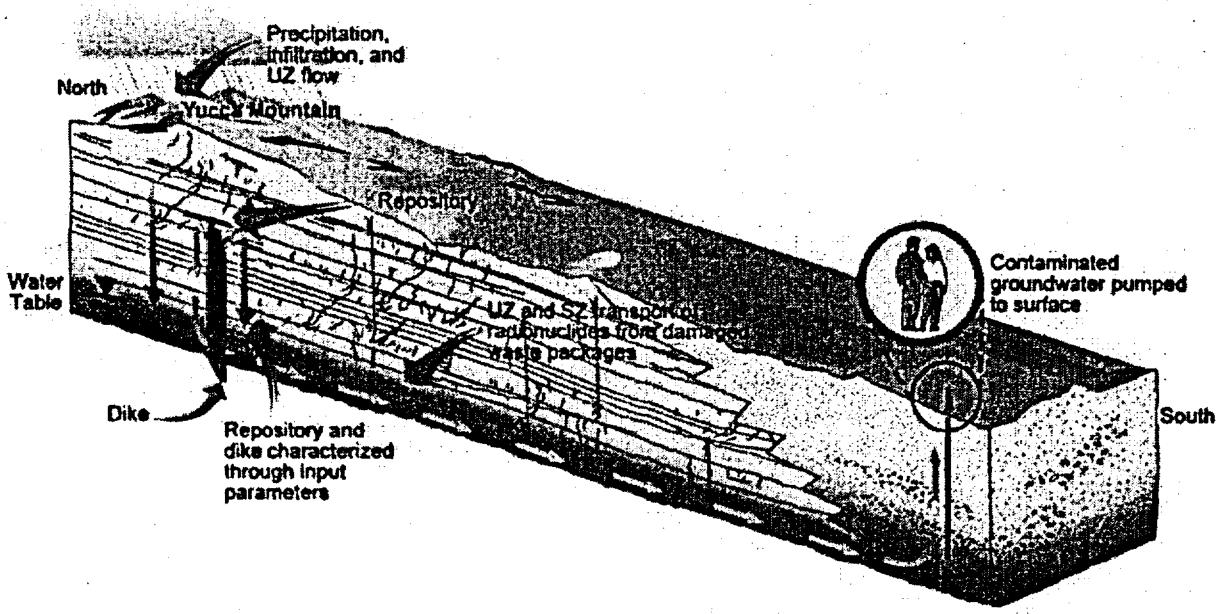


Figure 4-192. Schematic Diagram Showing an Igneous Intrusion at Yucca Mountain and Subsequent Transport of Radionuclides in Groundwater
UZ = unsaturated zone; SZ = saturated zone.

isolated section of the drift to the lithostatic pressure of the magma, further damaging the waste packages, and the dike will continue to propagate upward. Damage in the affected region will be severe, but it will be relatively minor further down the drift, behind the plug of backfill and debris.

For repository design alternatives that do not include backfill, damage within the drift will be much more extensive. Actual conditions are uncertain, but the pressure wave following decompression of the magma appears likely to propagate the full length of the affected drift. Immediate mechanical damage from the displacement of waste packages will be limited to the region around the point of intrusion, as in the backfill case, but damage to the drip shield and ground support will occur throughout the drift. More importantly, debris from the remains of the engineered barrier system may not be sufficient to create a plug within the emplacement drifts. Pyroclastic material (or liquid lava, in the case of extremely dry magma) could fill up to the entire length of the drift, and pressure could rise from atmospheric toward lithostatic before the dike can continue to propagate upward. The combination of high temperature (approximately 1,040° to 1,170°C [1,904° to 2,138°F]) and high pressure (approaching the magmatic lithostatic pressure of 7.5 MPa at the repository depth) could cause partial failure of the lid welds on affected packages. Therefore, for the no-backfill design, the TSPA-SR assumes that three packages on either side of the point of intrusion fail completely and that all other packages in drifts intersected by intrusive dikes are breached by cracks sufficient to allow pressure to equalize within the packages. Drip shields and cladding are assumed to fail completely in all drifts intersected by the intrusion. The number of drifts intersected is calculated probabilistically, based on the drift spacing and distributions for the azimuth and length of intrusive events.

4.4.3.3 Results and Interpretation

The approach taken in the TSPA models to calculating doses resulting from igneous disruption of the repository is consistent with the probabilistic methodology described in Section 4.4.1.[2] Scenario consequences are multiplied ("weighted") by the probability of the occurrence of the scenario to yield an appropriate estimate of the overall risk posed by low probability events.

Figure 4-193 shows a range of probability-weighted dose histories representing possible doses to a reasonably maximally exposed individual following disruption of the potential Yucca Mountain repository by igneous activity. Results do not include doses that might result from the nominal performance of the repository in the absence of igneous activity. These doses are discussed in Section 4.4.1. Results shown in Figures 4-193a and 4-193b are based on an analysis of 5,000 individual calculations, or realizations, using different sets of sampled values for uncertain input parameters in the model. Rather than showing the full set of 5,000 realizations included in the analysis, which would result in a display too dense to interpret, the figure shows 500 individual curves (in gray) that represent every tenth realization. The range of results shown by these individual curves displays the uncertainty in the calculated dose history that results from uncertainty in model parameter values.

Four additional curves, shown in color, provide summary information about the distribution of results from the full set of 5,000 realizations. The mean curve, shown in red, is the average probability-weighted annual dose rate. The percentile curves, shown for the 95th, 50th (i.e., median), and 5th percentile, show the annual dose rate that is greater than 95 percent (or 50 percent or 5 percent) of the calculated values at that time. The mean curve on Figure 4-193a lies above the 95th percentile curve throughout the interval between approximately 3,000 and 8,000 years because the mean is dominated by the relatively small fraction of the total number of realizations that contribute to a high groundwater dose rate at early times. The number of realizations contributing to this pathway increases through time as the cumulative probability of an intrusion having occurred increases, causing the 95th percentile curve to climb above the mean at later times.

Figure 4-194 shows the mean probability-weighted dose histories for the individual radionuclides that contributed to the total igneous dose rates shown in Figure 4-193a. These individual radionuclide doses are discussed in more detail in the following paragraphs in the context of the discussion of the mean total igneous dose history.

For approximately the first 2,000 years, the dose history is a smooth curve that is dominated by the effects of a volcanic eruption. As shown in Figure 4-193a, the probability-weighted mean total effective dose equivalent during this period reaches a peak of approximately 0.004 mrem/yr roughly 300 years after repository closure and then drops off due to radioactive decay of the relatively shorter-lived radionuclides that contribute to doses from the ash fall exposure pathway. As shown in Figure 4-194, the major contributors to the eruptive dose are americium-241 and plutonium-240, -239, and -238. Strontium-90 is a significant contributor at extremely early times, but drops off rapidly because of radioactive decay. Inhalation of resuspended particulates in the ash layer is the primary exposure pathway during this period and the smooth decline of the mean dose curve from approximately 300 to 2,000 years results from decay of americium-241, which has a half-life of 432 years.

From approximately 2,000 years after closure onward, the mean igneous dose is dominated by groundwater releases from packages damaged by igneous intrusion. The irregular shape of the curve from this point forward reflects the occurrence of intrusive events at random times, rather than the prescribed intervals used for the extrusive simulations. Close examination of Figures 4-193a and 4-193b shows that individual realizations display distinct peaks occurring at times that are controlled by the sampled time of intrusion and the time

[2] See Section 4.4.1 of *Issue Resolution Status Report Key Technical Issue: Total System Performance Assessment and Integration* (NRC 2000c), where the NRC describes the method for weighting consequences of individual scenarios by their probability before summing the scenario consequences to determine the overall expected annual dose. See also Reamer (1999, Section 3.4) for a discussion of the NRC's implementation of this approach for igneous activity.

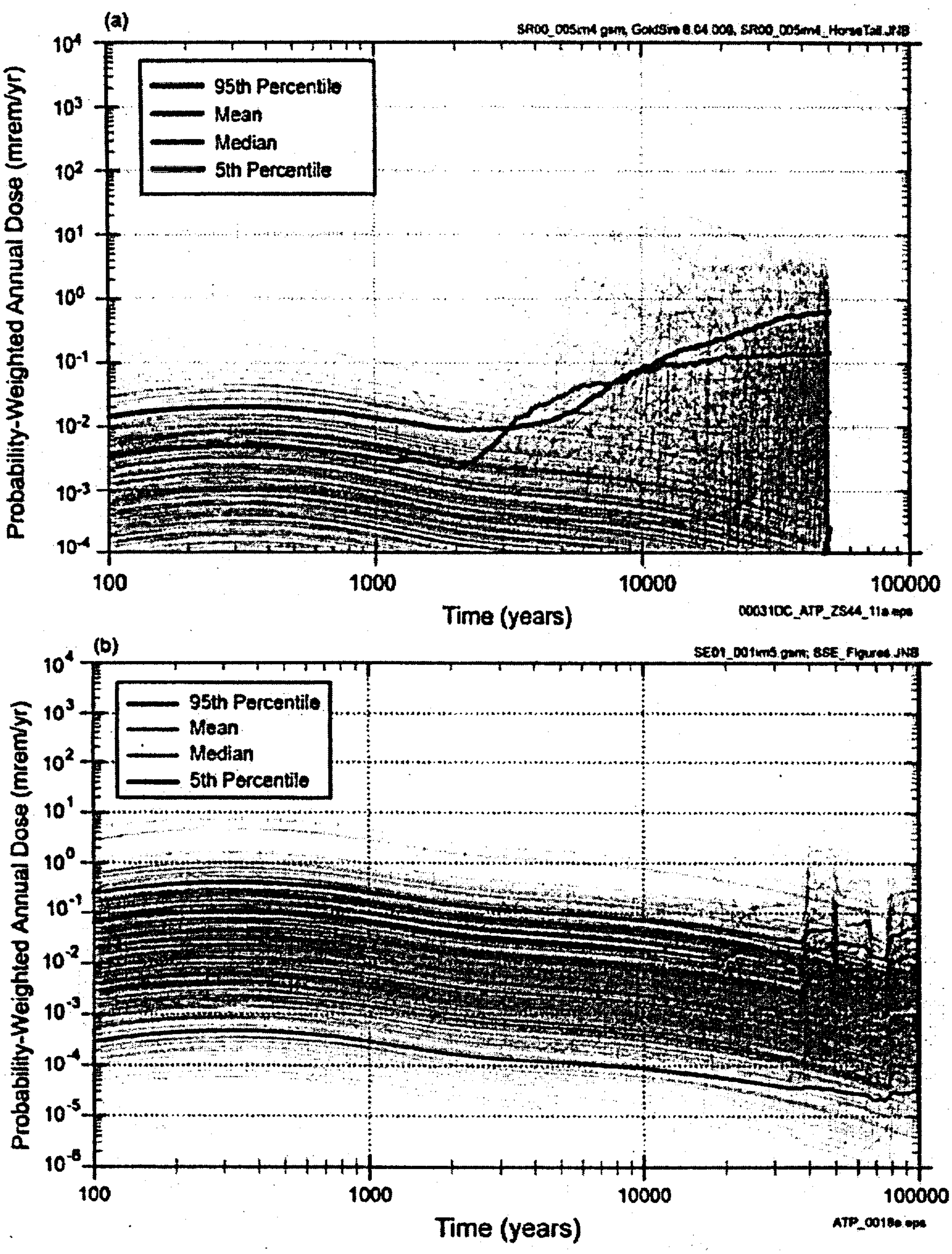


Figure 4-193. TSPA-SR Model and Revised Supplemental TSPA Models Results of Annual Dose to a Receptor for Igneous Activity Scenario

(a) Doses projected by the TSPA-SR model. (b) Doses projected by the revised supplemental TSPA model. Source: CRWMS M&O 2000a, Figure 4.2-1; Williams 2001a, Figure 6-10a.

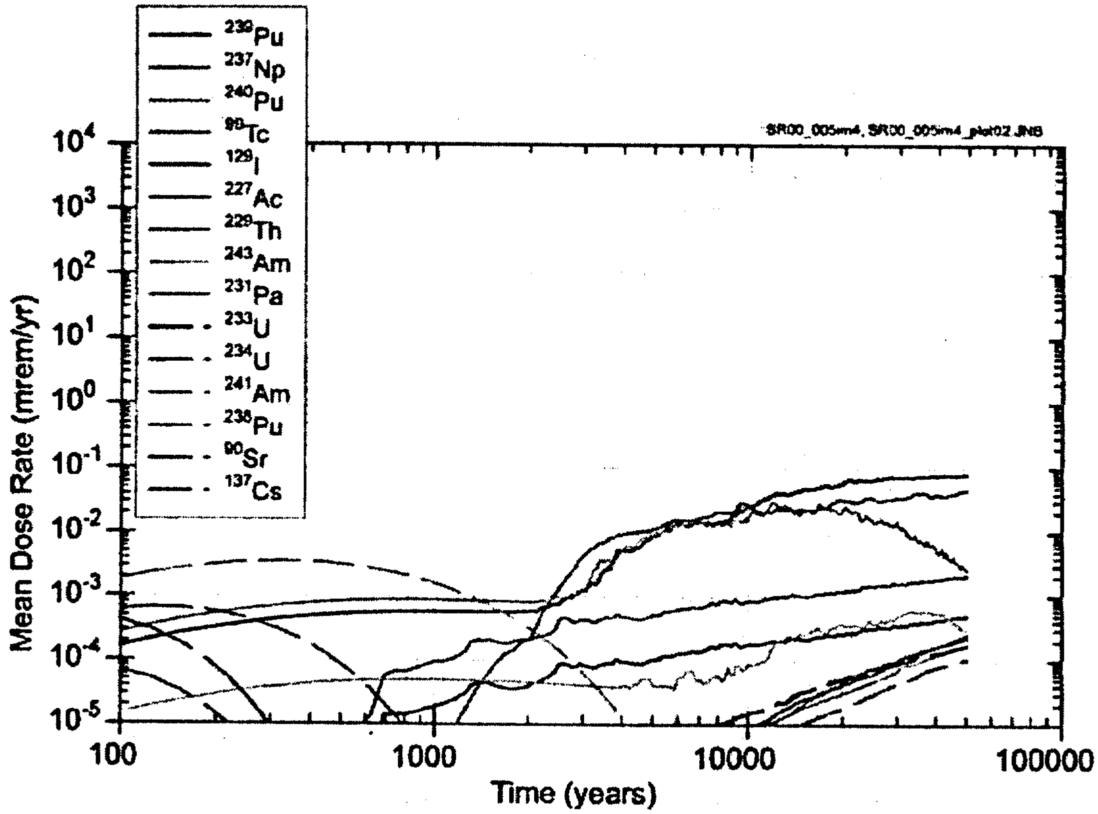


Figure 4-194. Igneous Dose Histories for Major Contributing Radionuclides Projected by the TSPA-SR Model
Source: CRWMS M&O 2000a, Figure 4.2-2.

required for radionuclide transport through the geologic system. The intrusive event may occur at any time, and the first appearance of groundwater doses in the mean curve at approximately 2,000 years reflects retardation during transport rather than the absence of intrusions at earlier times. The observation that some of the 500 individual curves continue to be dominated by the smooth, eruptive doses for essentially all of the 50,000-year period indicates either that, for those realizations, the sampled time of intrusion was relatively late or that, in some cases, retardation in the geologic system was effective for a relatively long period of time.

The overall probability-weighted mean igneous dose rate projected by the TSPA-SR model reaches a peak during the first 10,000 years of approximately 0.08 mrem/yr, occurring at 10,000 years. At later times, the calculated mean igneous dose rate is higher, increasing slowly to approach 0.2 mrem/yr at the end of the 50,000-year period. This peak mean igneous dose is dominated entirely by the groundwater releases following igneous intrusion. As shown in Figure 4-194, plutonium-239 and neptunium-237 are the primary contributors to the peak mean dose.

The probability-weighted dose histories projected for the disruptive scenario by the TSPA-SR model and the revised supplemental TSPA model are shown in Figure 4-195. The time histories are associated with a random occurrence of the disruptive events in the compliance period.

TSPA results for the volcanic disruptive scenario based on the TSPA-SR model, the supplemental TSPA model, and the revised supplemental TSPA model are summarized as follows:

- The TSPA-SR model projected a probability-weighted peak mean annual dose for the first

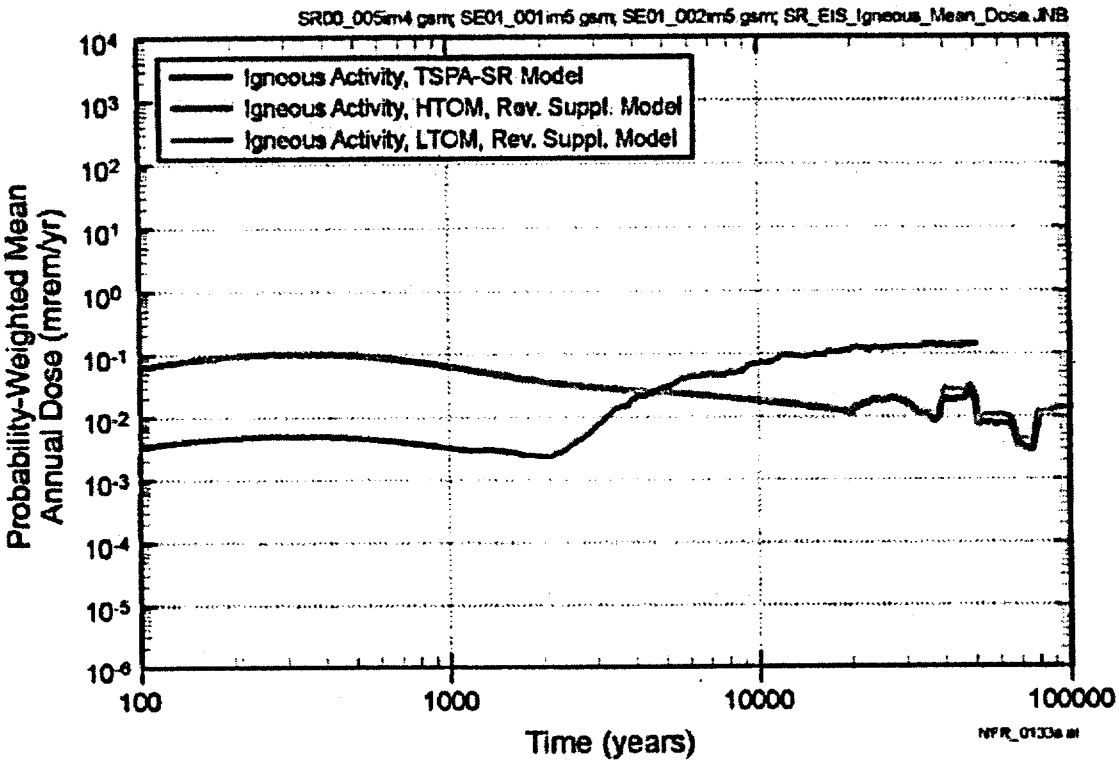


Figure 4-195. Projected Annual Doses for the Igneous Activity Disruptive Scenario
Probability-weighted mean annual dose histories are shown for the TSPA-SR model for the igneous activity scenario documented in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a). These results are presented along with revised supplemental TSPA model results for both higher-temperature operating mode (HTOM) and lower-temperature operating mode (LTOM), as documented in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a). Source: Williams 2001a, Figure 6-10c.

10,000 years of approximately 0.08 mrem/yr (occurring at 10,000 years) for the combined volcanic disruptive scenario (CRWMS M&O 2000a, Section 4.2.2). The dose history is dominated by the effects of volcanic eruption for about the first 2,000 years. After about 2,000 years, doses from volcanism are dominated by releases to the groundwater from waste packages damaged by igneous intrusion events. At that time, the projected doses from eruptive events gradually diminish due to the decay of the radioactive waste inventory in the repository (CRWMS M&O 2000a, Section 4.2.2).

- Model and parameter changes for the supplemental TSPA model for the volcanic disruption scenario class are described in Volume 1, Sections 13 and 14 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001a). Updated scientific information considered in the supplemental TSPA model increases the probability-weighted peak mean annual dose during the first 10,000 years to approximately 0.1 mrem/yr, which occurs about 300 years after closure (BSC 2001b, Section 4.3.1).

- The revised supplemental TSPA model was used to project probability-weighted peak mean annual dose to the reasonably maximally exposed individual. The probability-weighted peak mean annual dose projected for the combined volcanic disruption scenario (igneous intrusion and volcanic eruption) during the first 10,000 years using this model showed no change from the results projected using the supplemental TSPA model. Results were 0.1 mrem/yr for both the higher- and lower-temperature operating modes (Williams 2001a, Table 6-1).

Both the supplemental and revised TSPA models show the probability-weighted peak mean annual dose occurring approximately 300 years after closure and being dominated by doses from eruptive events for more than 10,000 years (BSC 2001b, Section 4.3.1; Williams 2001a, Figures 6-10b and 6-11b). The largest single contributor to the increase in the projected dose (compared to dose projected by the TSPA-SR model) comes from changes in biosphere dose conversion factors. Other factors include a change in wind speed, an increase in the conditional probability of an eruption at the repository location (from 0.36 to 0.77), and an increase in the total number of eruptive conduits possible within the repository (BSC 2001b, Section 4.3.1).

In the supplemental and revised supplemental TSPA models, after 10,000 years doses to the receptor (i.e., average member of the critical group for the supplemental TSPA models and reasonably maximally exposed individual for the revised supplemental TSPA model) following igneous intrusion are lower than the TSPA-SR model results, generally by a factor of five or more, with the TSPA-SR model peak mean dose from igneous intrusion occurring between 40,000 and 50,000 years after closure (BSC 2001b, Section 4.3.1; Williams 2001a, Figure 6-10c). Decreases in the probability-weighted annual dose from igneous intrusion are due to changes in the nominal scenario models for radionuclide mobilization and transport (BSC 2001b, Section 4.3.1). The distributions used to characterize uncertainty in the number of waste packages affected by igneous intrusion were modified, resulting in a larger number of packages damaged for the supplemental TSPA analyses conducted (BSC 2001a, Section 14.3.3.7; Williams 2001a, Section 6.1). This increase, however, is more than offset by decreases in radionuclide mobilization and transport (see Figure 4-195) (BSC 2001b, Section 4.3.1).

Results from revised supplemental TSPA model analyses also show that thermal operating conditions have no effect on the doses from the eruptive case. Higher- and lower-temperature operating mode curves overlay each other until releases (resulting from igneous intrusion) begin to cause noticeable divergence after about 20,000 years, when mean annual dose for the lower-temperature operating mode becomes greater than the dose from the higher-temperature operating mode by up to a factor of 3 (BSC 2001b, Section 4.3.1; Williams 2001a, Figure 6-10c).

These interpretations of the performance results for the disruptive scenario are valid for the wide range of quantifiable uncertainties that were considered in TSPA models. The TSPA results for the disruptive scenario are presented in more detail and fully documented in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a, Section 4.2), Volume 2, Section 3.3.1 of *FY01 Supplemental Science and Performance Analyses* (BSC 2001b), and *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Section 6.3).

4.4.3.4 Combined Releases from the Nominal and Disruptive Scenarios

To combine the expected annual doses from the nominal and disruptive scenarios, the dose for each scenario was weighted by the scenario probability, so the summed expected annual dose includes both consequence and probability and, therefore, represents the expected risk for the repository. The DOE calculated the annual dose to the reasonably maximally exposed individual as a result of releases from the Yucca Mountain disposal system (considering nominal and disruptive scenarios) that are projected to occur during the first 10,000 years, consistent with EPA and NRC regulations for individual protection (see 40 CFR Part 197 and 10 CFR Part 63 [66 FR 55732]).

The revised supplemental TSPA model calculations supporting the evaluation of individual protection were performed within a probabilistic framework combining the most likely ranges of behavior for the various component models, processes, and corresponding parameters in the process models describing repository performance. The TSPA analyses evaluated both the nominal scenario (70,000 MTHM) and the disruptive scenario (igneous activity) under both the higher- and lower-temperature operating modes (Williams 2001a). The nominal scenario was analyzed by operating the revised supplemental TSPA model for 300 realizations, and the disruptive scenario was analyzed using 5,000 realizations (Williams 2001a, Sections 6.2.1 and 6.3).

The mean annual dose from the results of the model simulations using the revised supplemental TSPA model is presented in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Figure 6-14). Table 4-37 summarizes the results of these simulations and shows the peak mean annual dose for the nominal and disruptive scenarios for both higher- and lower-temperature operating modes. Table 4-37 presents the peak 95th percentile dose for the multiple realizations for the same cases. These data provide confidence in the expected repository performance because 95 percent of the realizations yielded a peak dose that are less than the values shown on the table. For example, the 10,000-year peak 95th percentile value for the disruptive scenario (igneous-activity case), higher-temperature operating mode, is 4.1×10^{-1} mrem/yr, indicating that 4,750 of the 5,000 realizations for that case had a peak value less than 4.1×10^{-1} mrem/yr, and only 250 realizations resulted in a peak value higher than 4.1×10^{-1} mrem/yr. Further, examination of the plots presented in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a, Figures 6-10a and 6-11a) shows that the peak annual dose for all realizations is less than 10 mrem/yr.

For purposes of individual protection (combined nominal and disruptive scenario), the revised supplemental TSPA model calculated doses consistent with the final EPA rule at 40 CFR 197.21 as discussed in *Total System Performance Assessment—Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain—Input to Final Environmental Impact Statement and Site Suitability Evaluation* (Williams 2001a). Dose is calculated to the reasonably maximally exposed individual, a hypothetical person, located at the point above the highest concentration of radionuclides in the simulated plume of contamination where the plume crosses the southernmost boundary of the controlled area (at a latitude of 36° 40' 13.6661" North) and reaches the accessible environment. This distance is approximately 18 km (11 mi) from the repository footprint, compared to the original distance of approximately 20 km (12 mi) used in the saturated zone transport modeling calculations supporting the TSPA-SR model and supplemental TSPA model analyses.

Table 4-37. Tabulated Peak Mean Annual Dose and Peak 95th Percentile Dose for the Nominal Case and the Disruptive (Igneous Activity) Case

Peak Mean Annual Dose		
	10,000-Year Peak	
Case	Value (mrem/yr)	Year
70,000 MTHM, HTOM	1.7×10^{-5}	4875
70,000 MTHM, LTOM	1.1×10^{-5}	3438
Igneous Activity, HTOM	1.0×10^{-1}	313
Igneous Activity, LTOM	1.0×10^{-1}	313
Peak 95th Percentile Annual Dose		
	10,000-Year Peak	
Case	Value (mrem/yr)	Year
70,000 MTHM, HTOM	1.2×10^{-4}	4938
70,000 MTHM, LTOM	8.8×10^{-5}	5000
Igneous Activity, HTOM	4.1×10^{-1}	313
Igneous Activity, LTOM	4.1×10^{-1}	313

NOTES: These data are based on the same probabilistic annual water usage model used in the TSPA-SR, and would be approximately 1/3 lower if 3,000 acre-feet/yr was used, consistent with NRC regulations model (not 3,000 acre-ft/yr).
HTOM = higher-temperature operating mode; LTOM = lower-temperature operating mode.
Source: Williams 2001a, Table 6-1.

The revised supplemental TSPA model utilized a slice-of-the-plume method to calculate the dose to the reasonably maximally exposed individual based on an average annual water demand of 2,000 acre-ft of groundwater. Using this method, 100 percent of the released radionuclides reaching the accessible environment are contained in that groundwater volume which represents the amount of water that would be withdrawn and used annually by the reasonably maximally exposed individual. This method minimizes the effects of natural dilution processes that would occur along the flow path and bounds potential consequences. This volume of water was an average volume necessary to operate 15 to 25 farms, representing a range of groundwater volumes from 887 to 3,367 acre-ft, consistent with proposed 10 CFR 63.115 (64 FR 8640). In addition, the revised supplemental TSPA model, consistent with 40 CFR 197.21, used a daily average groundwater consumption of 2.0 L (0.53 gal), compared to the daily average groundwater consumption volume of 2.1 L (0.55 gal) in the earlier TSPA models.

The calculated peak mean annual doses over the first 10,000 years for the nominal scenario using the revised supplemental TSPA model are thousands of times smaller than the probability-weighted mean annual dose for the disruptive scenario. Therefore, the combined mean annual dose for comparison with individual protection standards as calculated by the revised supplemental TSPA model is approximated as the probability-weighted mean annual dose from the disruptive scenario, or 0.1 mrem/yr, during a 10,000-year period (Williams 2001a, Section 6.2 and Table 6-1). This is the calculated dose for both the higher- and lower-temperature operating modes, as shown in Figure 4-190.

It is noted that the final NRC individual protection standard specifies an annual water demand of 3,000 acre-ft (10 CFR 63.312(c) [66 FR 55732]). An average annual water demand of approximately 2,000 acre-ft was used in the TSPA-SR and supplemental and revised supplemental TSPA analyses. The TSPA analyses assumed that 100 percent of the released radionuclides reaching the accessible environment is contained in that groundwater volume for use and consumption. The TSPA mean doses calculated for the evaluation of individual protection, therefore, represent conservative (higher) estimates. Doses from the groundwater-pathway-dominated scenarios would be reduced by about one-third using an annual water demand of 3,000 acre-ft. The effects on dose calculations of an annual water demand of 3,000 acre-ft are discussed further in *Total System Performance Assessment Sensitivity Analyses for Final Nuclear Regulatory Commission Regulations* (Williams 2001b, Section 6.3).

The TSPA results can be summarized as follows:

- Initial calculations for individual protection used the TSPA-SR model. The probability-weighted mean peak dose occurring within the first 10,000 years, as calculated by the TSPA-SR model was approximately 0.08 mrem/yr, resulting from the disruptive scenario (Figure 4-195). The nominal scenario showed no projected dose to a receptor in the 10,000-year period (CRWMS M&O 2000b, Section 4.2.2). Therefore, the combined nominal plus igneous activity dose over the 10,000-year period is 0.08 mrem/yr.

- The supplemental TSPA model results show the peak mean annual doses for both the higher- and lower-temperature operating modes over the 10,000-year period are approximately 0.1 mrem/yr, resulting from the disruptive scenario (BSC 2001b, Section 4.3).

- Results using the subsequent revised supplemental TSPA model were the same (Williams 2001a, Table 6-1). Because the calculated mean annual doses over the 10,000-year period for the nominal scenario (2×10^{-4} mrem/yr for the higher-temperature operating mode and 6×10^{-5} mrem/yr for the lower-temperature operating mode) are thousands of times smaller than the probability-weighted mean annual doses for the disruptive scenario, the combined mean annual doses, when rounded, are the same as the probability-weighted peak mean annual dose from the disruptive scenario (0.1 mrem/yr during the first 10,000 years) (see Figure 4-190).

4.4.4 Assessment of Human Intrusion Scenario

4.4.4.1 Background

The stylized human intrusion scenario performed by the TSPA-SR model can be summarized as follows:

- The human intrusion occurs at 100 years after permanent repository closure, consistent with proposed NRC regulations.
- The intrusion results in a single, nearly vertical borehole that penetrates a waste package and extends down to the saturated zone.
- Current practices for resource exploration are used to establish properties (e.g., diameter of the borehole, composition of drilling fluids).
- The borehole is not adequately sealed to prevent infiltrating water, and natural degradation processes gradually modify the borehole.
- Only releases through the borehole to the saturated zone are considered; hazards to the drillers or to the public from material brought to the surface by the assumed intrusion are not included.

These features of the human intrusion scenario are illustrated conceptually in Figure 4-196, and key aspects and technical assumptions are given in Table 4-38.

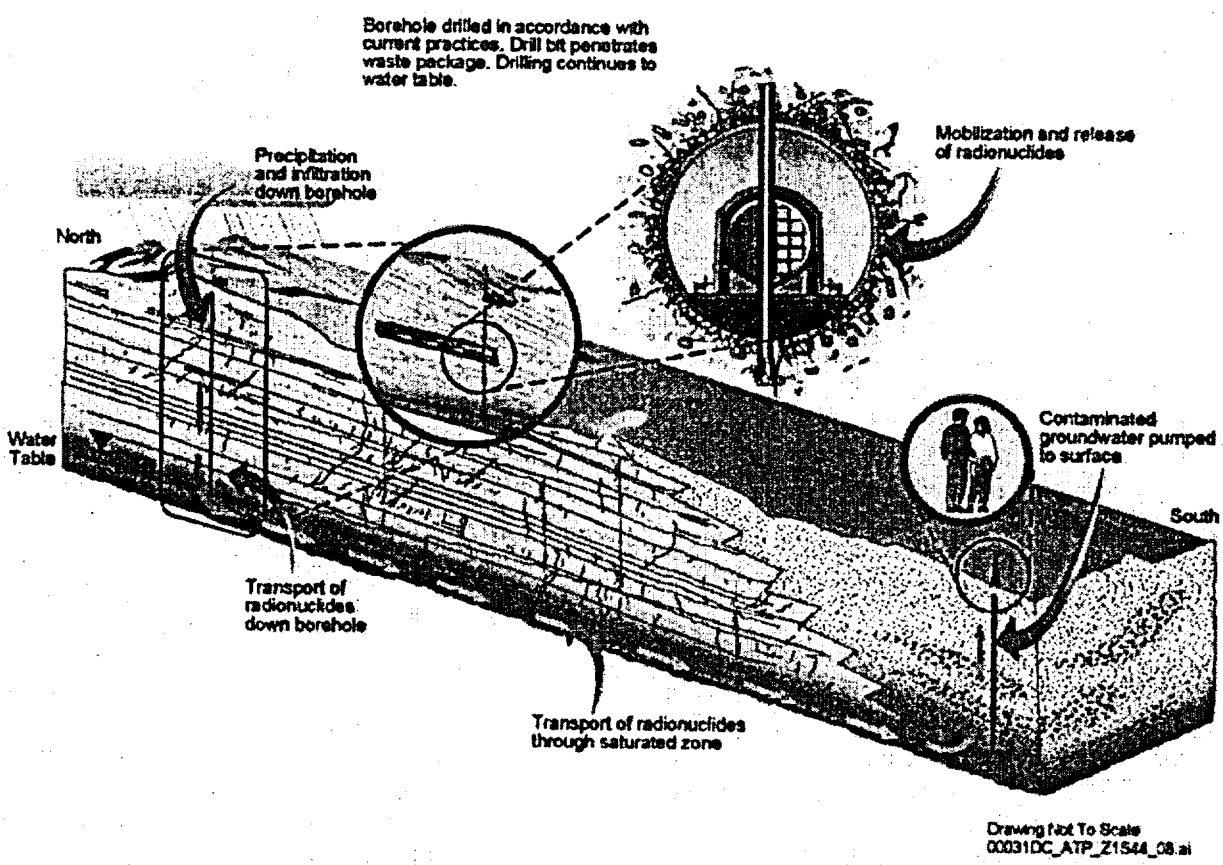


Figure 4-196. Conceptualization of Human Intrusion Scenario in the TSPA-SR Model