Chapter 2
Unsaturated Zone

I. Overview

If the Yucca Mountain site is deemed suitable for repository development, the repository will be constructed in the UZ in welded tuff at a depth of about 300 meters below the land surface and a distance of approximately 300 meters above the regional water table. The potential repository block is composed of welded and nonwelded tuffs[1] that are 11 to 13 million years old. The block is bounded by the Ghost Dance fault on the east and the Solitario Canyon fault on the west. Smaller faults not exposed at land surface may be present within this block. Largely on the basis of the extent of welding, the tuffs within the UZ at Yucca Mountain are grouped informally into hydrogeologic units that, from the surface down, are the Tiva Canyon welded (TCw) unit, the Paintbrush nonwelded (PTn) unit, the Topopah Springs welded (TSw) unit, the Calico Hills nonwelded (CHn) unit, and the Crater Flat undifferentiated (CFu) unit. The host rock at the potential repository horizon consists primarily of densely welded tuff within the TSw unit. The general geologic structure of the region near Yucca Mountain is illustrated in Figure 2-1 on page 14.

A. Why UZ Was Chosen

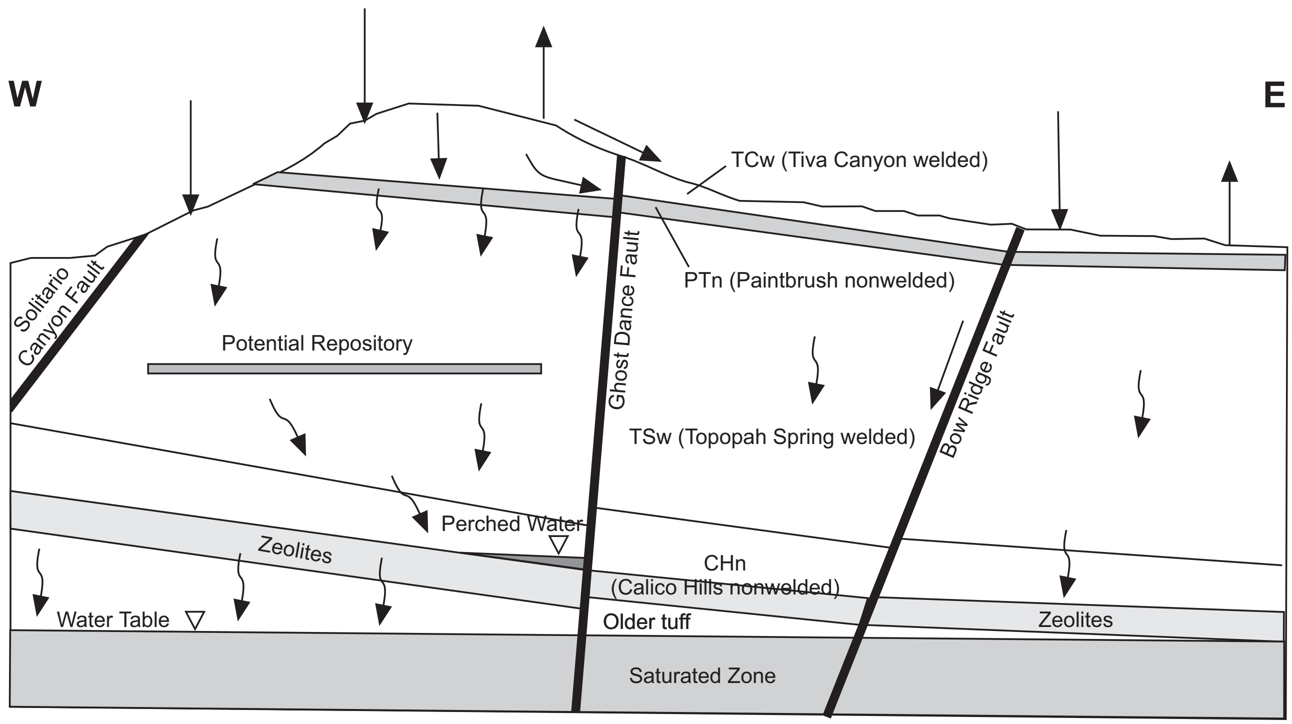
Initial studies of Yucca Mountain as a potential site for a nuclear waste repository were performed by the USGS (e.g., Winograd 1981, Roseboom 1983). USGS scientists believed that several key attributes of the UZ at Yucca Mountain are especially useful for waste isolation. For example, Yucca Mountain is a relatively arid site, and much of the precipitation is lost to runoff and evapotranspiration.[2] Net infiltration, the fraction of the precipitation that enters the mountain, is very small, as is the amount of water that can percolate down to the repository horizon. Some of the percolating water could seep into repository tunnels, where it could corrode waste packages and eventually mobilize part of the waste. Because the TSw is densely fractured, it is well drained, so water accumulation and flooding of the repository are highly improbable.

The regional water table is known to have risen no more than about 100 meters above present levels during pluvial periods (wetter and cooler than the present). The position of the paleo (prehistoric) water table was well below the level of the proposed repository horizon.

On the basis of the early studies, Montazer and Wilson (1984) of the USGS synthesized the UZ hydrology (net infiltration, percolation) and physical rock properties. They reached the following conclusions:

1. Tuff is a rock formed by consolidation of hot volcanic ash. Welded tuff has been fused and hardened by heat, pressure, and possibly the introduction of cementing minerals. Welded tuff contains more fractures than does nonwelded tuff.
2. Evapotranspiration includes direct evaporation of water from soil and movement of water from soil to air by plants.

Figure 2-1. East-West Cross Section of Yucca Mountain Area (after U.S. DOE 1998)



- Precipitation was estimated to be about 150 millimeters per year (mm / yr).
- Net infiltration is spatially and temporally heterogeneous and was estimated to average about 0.5 to 4.5 mm / yr, based on comparisons with other arid environments.
- The PTn unit could divert up to 100 mm / yr, but the actual amount of diversion was unknown.
- A maximum of ~0.2 mm / yr of water could be flowing in the matrix of the TSw unit, but the flux in the fractures was unknown.

The low flux[3] of water in the TSw unit was not the only favorable characteristic expected for the UZ. In addition, if radionuclides are released from the EBS, their travel time through the UZ to the water table was estimated as 9,000 years or more (DOE 1988). This was due to the slow velocity of water movement in the partially saturated rock matrix and the potential retardation by sorptive minerals, such as zeolites, in the underlying CHn. These perceived favorable natural attributes of the UZ, in addition to the long-term waste containment anticipated for the waste packages, were to provide defense-in-depth for long-term waste isolation at Yucca Mountain. These favorable attributes also led to a bias against further study of the SZ.

B. Current Role of UZ in DOE's Repository Safety Strategy

Performance assessments have shown that the volume and geochemistry of the water that may reach waste packages, cause corrosion, mobilize the waste, and carry radionuclides to the water table are

3. "Flux" means the rate at which groundwater flows through the ground or, more specifically, the volume of flow per unit area of ground perpendicular to the direction of flow.

key scientific issues in long-term isolation of radioactive waste. Three of the key attributes[4] of the DOE's repository safety strategy (DOE 1998) derive, at least in part, from the assumption that Yucca Mountain is an environment where the precipitation is low, the amount of water entering the ground is small, and the volume of water that can enter the tunnel openings (seepage) is limited by capillary forces that hold the water in the rock matrix. Recent information indicates, however, that more water may enter the mountain than previously expected and that some of this water flows through the mountain rapidly. The implications of this information are discussed in this chapter.

II. Net Infiltration of Water at Yucca Mountain

"Net infiltration" is defined as water that penetrates to sufficient depth so that it is not removed from the ground through evapotranspiration. Net infiltration varies both spatially (influenced by precipitation, elevation and slope exposure, type and thickness of soil, vegetation, bedrock permeabilities) and temporally (magnitude and timing of storm events and longer-term climate change). Because of the many variables that influence net infiltration, it is a quantity that is very difficult to measure directly, requires a long period of observation, and thus always will have a significant uncertainty. The DOE has collected extensive data over the last 10 years and has conducted modeling to assess the amount and distribution of precipitation and infiltration. Based on site-specific precipitation records, in situ saturation measurements, and local geologic conditions, a map of net infiltration was developed for Yucca Mountain (Flint, Hevesi, and Flint 1996).

Infiltration is an episodic process linked to the occurrence of a major storm event or a sequence of storm events. The greater the storm event, the more infiltration can be expected. Between these episodic storm-related infiltration events, there is little or no infiltration. Because of the episodic nature of large infiltration events and their relative infrequency (from years to a few tens of years or more), a long precipitation record is needed to provide the data for forecasting future occurrences.

A panel of scientists having expertise in UZ hydrology was formed to evaluate available hydrologic information about Yucca Mountain. The Unsaturated Zone Flow Model Expert Elicitation (UZFMEE) Project Panel assessed the acquired data and associated modeling of infiltration. Their aggregate estimate of the temporal and spatial mean (average) net infiltration over Yucca Mountain was 8 to 9 mm/yr, with 5th and 95th percentiles of tenths of millimeters per year and several tens of millimeters per year, respectively. The probability distributions that were elicited from the individual panel members exhibited even larger variances. In those estimates, the temporal average comprises periods of time long enough to include several episodic infiltration events, e.g., the last 50 to 100 years. During the wetter and colder climates that occurred in the last 10,000 years, the net infiltration undoubtedly was greater (UZFMEE 1997).

III. Percolation Flux

Percolation flux is the part of the net infiltration that eventually flows down to the repository horizon. The DOE long has understood that percolation flux is an important site-specific quantity that affects repository performance. If the percolation flux is sufficiently small, then capillary forces can be assumed to keep most of the flow within the rock matrix, and only an insignificant part of the percolation flux can seep into the tunnels (seepage flux). In this case, very little water will contact the waste packages, ensuring long waste package lifetimes, slow waste mobilization, and a slow rate of radionuclide release from the engineered barriers.

4. The four key attributes of the repository safety strategy are (1) limited water contacting the waste packages, (2) long waste package lifetime, (3) slow rate of release of radionuclides from the waste form, and (4) concentration reduction during transport through engineered and natural barriers. The first three depend, at least in part, on limited availability of water in the Yucca Mountain UZ.

Because the percolation flux is now expected to be greater than assumed in the past and because the flux is expected to be even greater during future pluvial (high rainfall) climate conditions, both theoretical and experimental investigations are being carried out to determine a relationship among percolation flux, rock properties, and seepage flux (discussed below). This work should be completed within the next few years and will allow a better estimate (bound) on seepage flux for various climatic conditions.

A. UZ Site-Scale Model

Because of the heterogeneous nature of flow in the UZ, the percolation flux has not been measured, and cannot be expected to be measured, over extensive scales in time and space. It must be modeled numerically on the basis of surface and near-surface observations and extrapolated to greater depths. A UZ site-scale model has been developed and calibrated by Lawrence Berkeley National Laboratory (LBNL) and the USGS for this purpose (Bodvarsson, Bandurraga, and Wu 1997). This numerical model uses infiltration data and results from infiltration models as its basic input; it then simulates the movement of the infiltrating water down to the repository horizon. The model has been calibrated, to various degrees, to almost all relevant data collected on the UZ at Yucca Mountain. As new data on air permeabilities, temperature profiles, or isotopic ages of waters are acquired, they are incorporated in the model. The percolation flux at and below the repository horizon is the primary output of this model and is the essential input to other models for estimating seepage flux and computing radionuclide transport.

The following caveat is important: Modeling the flow of groundwater through unsaturated fractured rocks is an uncertain proposition by itself, independent of all other uncertainties. This is because unsaturated fractured rocks exhibit extremely strong spatial heterogeneities in their physical and fluid-flow properties. A growing body of evidence shows that a fraction (as yet undetermined) of water flow may take place through localized flow along preferential paths, such as fractures. Mathematical models may not be able to represent localized flow paths realistically if they average hydrologic properties over volumes larger than the dimensions of the flow paths. Thus, there is uncertainty about the approximation one makes in using large-scale volume-averaged differential equations to model this type of spatially variable and episodic flow at Yucca Mountain. This caveat has been known for a long time and has been raised often during the years (UZFMEE 1997).

Uncertainty about the UZ site-scale model should be investigated by considering alternative conceptual approaches. Some models, such as the so-called “weeps” model, although simple and transparent, can capture the essential physics of preferential flow paths. Mechanistic models of flow and transport, on the other hand, represent (statistically) the detailed heterogeneity of the rock and of the flow system. Use of these complementary approaches to the present modeling would provide a higher level of confidence that the essential physics of UZ flow is adequately represented by the current conceptual approach.

B. Lateral Diversion of Infiltration at PTn Unit

In the absence of long-range (regional) lateral diversion at the PTn unit, the average percolation flux should equal the average net infiltration over Yucca Mountain. A capillary barrier[5] may exist between the welded TCw unit and the underlying nonwelded PTn that could divert moisture laterally downdip along the contact between the two units (Montazer and Wilson 1984; Moyer, Geslin, and Flint 1996). Some lateral flow also could occur at the contact between the PTn and the underlying welded TSw (UZFMEE 1997, individual elicitations). The hypothesis of long-range lateral diversion of water at the PTn was readily accepted by the project (i.e., the “tin roof” hypothesis). Thus, the percolation flux through the repository horizon was assumed to be very low (~0.2 mm/yr was a DOE and M&O position documented in the initial draft versions of the waste isolation strategy).

5. If two geologic strata have different pore sizes, capillary forces will tend to hold water in the stratum with smaller pores and prevent it from moving into the stratum with larger pores.

This assumption was called into question when A.L. Flint (USGS) presented his net infiltration map at the Board's hydrogeology and geochemistry panel meeting in San Francisco in June 1995 (Flint 1995). At that time, Flint's data and model computations suggested that the average infiltration flux over Yucca Mountain for the last 10 years was closer to 15 mm / yr, implying that the lateral diversion at the PTn would have to be extremely effective to keep the percolation flux at such a low value (~0.2 mm / yr).

Although this PTn diversion hypothesis was questioned, no conclusive data were available to support or dismiss the hypothesis until the discovery of bomb-pulse ^{36}Cl in the ESF at the repository horizon. If the ^{36}Cl data proved reliable, it was clear that fast pathways must exist through the PTn to the repository horizon. That is, the PTn appeared to act more like a torn blanket than a tin roof. In addition, most flow models being used by the project required a much larger percolation flux if the water was to travel to the ESF in less than 50 years (Fabryka-Martin et al. 1997).

Additional data, analysis of numerous calcite deposits in fractures (Peterman and Paces 1996), chloride mass balance, and analysis of thermal data led to a revised estimate of percolation flux. During the October 1996 Board meeting, G. S. Bodvarsson's presentation (Bodvarsson 1996) summarized the preponderance of data that indicate that the present average percolation flux over the repository footprint (~6-10 mm / yr) is significantly higher than previously assumed (~0.1-0.2 mm / yr).

C. Percolation Flux: Variability and Uncertainty

Because percolation flux is temporally and spatially heterogeneous, all stated values are averages over some spatial and temporal domain. Although some lateral diversion can occur at the PTn unit, this diversion is thought to be only on the order of tens of meters or so (UZFMEE 1997). Because of the fracturing and heterogeneity of the PTn unit, the present assumption is that the PTn does not divert infiltration from the repository but simply smoothes out the episodic pulses of infiltration, so percolation flux appears more uniform in space and time than infiltration flux at the surface.

On the basis of data presented to it, the UZFMEE panel believed that the average percolation flux is approximately equal to the average net infiltration (approximately 10 mm / yr). Their estimate of uncertainty for the average percolation flux over Yucca Mountain was ~1 mm / yr to ~30 mm / yr. These values can be considered the 5th and 95th percentile values of a distribution whose mean is ~10 mm / yr and median is ~7 mm / yr (UZFMEE 1997).[6] The strong spatial variability in the percolation flux implies that there can be very large localized fluxes of water, e.g., 50 mm / yr or more. Bomb pulse ^{36}Cl data are evidence of such pulses through isolated fast paths. Yet, these pulses may be carrying only a small fraction (~1 percent to 5 percent or so) of the total flow. The spatial variability of the percolation flux and the distribution of fast paths can affect the number of waste canisters that are contacted and thus can affect repository performance. The weeps model of flow in the UZ was intended to capture the concept of isolated fast-path fracture flow, but separating out the effects of natural variability and data uncertainty when describing percolation flux is exceedingly difficult.

IV. Seepage into Tunnels

There is a large uncertainty about the fraction of the percolation flux that will drip into the emplacement tunnels (i.e., the seepage flux) and contact the waste packages. Of the natural characteristics of Yucca Mountain that would affect repository performance, seepage flux into tunnels at the repository horizon is the most important. This is because the amount, timing, and chemistry of water entering the tunnels can have an important effect on the environment of the waste packages and other engineered barriers, including relative humidity and possible dripping

6. The estimated percolation flux varies slightly from the estimated infiltration discussed earlier only because of differences in the numbers of experts who provided estimates for each parameter.

onto the waste package. Seepage flux is therefore an important determinant of the rate at which radionuclides can be mobilized from the waste form and released from the repository.

A. Seepage Under Ambient Conditions

Seepage is most likely to occur when a flowing fracture intersects an emplacement tunnel, resulting in local accumulation of water (local saturation) and leading to dripping into the tunnel. Under ambient conditions, the general expectation is that a relatively small fraction of the present percolation flux will enter the tunnels. Capillary forces will tend to keep the water within the host rock and divert the flow around the tunnels (UZFMEE 1997). Data are being acquired by the project to test this hypothesis and quantify the relationship between percolation flux and seepage flux.

Preliminary numerical modeling of seepage supports this expectation. These computations also show that as the percolation flux increases to values higher than 100 mm / yr, seepage becomes a progressively larger fraction of the percolation flux. These computations are very sensitive to local rock properties, such as rock heterogeneity—the more heterogeneous the rock properties, the larger the seepage for a given percolation flux. Thus, any rockfalls within tunnels could increase seepage of water into the tunnels.[7] Additional sensitivity studies, supported by the proposed seepage experiments in the east-west tunnel and other locations underground, will improve understanding and provide better bounds on the relation between percolation and seepage within the next few years.

B. Seepage During Thermal Period

If the repository is designed for a high thermal load, significant water movement may occur around the emplacement tunnels during the early, high-temperature regime. As temperatures in the host rock rise above the boiling point, water will vaporize in the matrix and move through permeable fractures to cooler, lower-pressure areas. There, the vapor will condense and flow downward from the point of condensation, possibly into emplacement tunnels.

The consequences of this complex hydrologic response are difficult to predict, especially during the early heating period. The flow is transient and episodic and is highly dependent on rock heterogeneity. Will the water removed from the host rock drain around the emplacement tunnels, maintaining a dry-out (high temperature, low relative humidity) region around the tunnels? Or will a significant amount of this mobilized water penetrate the dry-out region and enter the tunnels? Mathematical models, because of their smoothing or averaging tendencies, have difficulty representing these complex, transient phenomena. Over a longer period of time, one type of model (a dual-permeability model) predicts that the mobilized water eventually will drain around an emplacement tunnel and that a local dry-out will be achieved. This is what has been observed in the single-heater test. However, another type of model (a single effective continuum model) predicts accumulation of water above the tunnel and no draining around the tunnel. Neither model is capable of predicting realistically how much water could enter the tunnels when repository temperatures are high.

Currently, the question, "How much water will be entering the tunnels during the thermal episode?" has not been answered by model computations or experiments. The completed single-heater test and the much larger drift-scale (tunnel-scale) test that began on December 6, 1997, were designed in part to address these questions. The single-heater test has provided useful information on the movement of water—that is, mobilized water eventually drains around the heated tunnel, and a dry-out region is formed. The hope is that the drift-scale test will provide similar types of data on a much larger scale and for a different geometry in the next several years.

7. The N-tunnel complex at the Nevada Test Site is a potential source of useful data on seepage into tunnels. Located at a much higher elevation, it is in an area of much higher precipitation and thus infiltration. The N-tunnel complex may provide a natural analog of seepage at Yucca mountain in anticipated wetter climates in the future.

C. Seepage After Thermal Period

After the thermal episode, which is expected to last more than a thousand years, it is highly probable that some rockfalls will have occurred in the tunnels, potentially increasing seepage of water into the tunnels. On a still longer time scale, such as 1 million years, the probability increases that seismically induced rockfall will have occurred within the tunnels (Barnard 1998). It also has been *postulated* that there will be rock alteration in the near field because of thermally induced hydrologic-chemical processes and that this alteration could change the permeability and other rock properties. Seepage after the thermal period, under these altered near-field conditions, has not been investigated thoroughly, to the Board's knowledge. Certain engineered barriers (enhancements) are being considered, such as backfill, that could mitigate to a certain extent the uncertainties in seepage after the thermal period.

V. Conceptual Model of Radionuclide Transport in UZ

A. Fracture-Matrix Flow in UZ

After radionuclides are released from the EBS to the host rock, they will be transported by the downward-percolating water to the SZ. The heterogeneous nature of the UZ implies that there will be large variability in radionuclide travel times to the SZ, ranging from very fast in fractures to very slow in the rock matrix.[8] The average travel time to the SZ through the low-permeability rock matrix is very long, more than 10,000 years. Such a long travel time would provide defense-in-depth against any unanticipated early release of radionuclides from the EBS. The last few years have shown clearly, however, that when there is a sufficiently large infiltration pulse of water, the water can reach the repository horizon in less than 50 years (Fabryka-Martin et al. 1997). Recently, the association between such "fast pathways" and geologic structure has been corroborated further by the numerous findings of ^{36}Cl and tritium in an alcove excavated from the ESF into the Ghost Dance fault (Fabryka-Martin et al. 1998).

As modeled by the project, the TSw matrix transmits 0.3 to 3.0 mm / yr at most. The remainder of the percolation flux is assumed to flow in fractures (Bodvarsson, Bandurraga, and Wu 1997). As the percolation flux increases, the volume of flow in fractures increases. The presence of bomb-pulse ^{36}Cl at depth can be explained best by the existence of such fast flow paths, although these data cannot be used for directly ascertaining how much of the total flow this represents. There are insufficient data for determining the distribution of travel times through the UZ. The present ^{36}Cl data indicate only that some water has reached the ESF in less than 50 years but not how much of the total flow these data represent.

B. Retardation

A principal transport parameter used by the TSPA is the sorption coefficient (K_d) for a specific radionuclide, which quantifies the degree of sorption of the radionuclide on a specific mineral surface. The net effect is to slow transport of the radionuclide—very significantly in many cases. Retardation can play a very significant role in delaying the arrival of neptunium and plutonium at the accessible environment. However, verifying to what degree this process will be important in situ is a more difficult problem. When flow occurs through fractures or other fast paths, retardation by sorbing minerals may not be as effective as it is for flow through the rock matrix.

In initial concepts of a Yucca Mountain repository, minerals called "zeolites" that are present within the CHn were viewed as a potential barrier because of their high sorptive capabilities. The assumption was that released radionuclides moving down through the CHn would be sorbed on the zeolites and other mineral surfaces and would be retarded significantly, resulting in extremely long travel times to the SZ. If there are fractures or fast pathways

8. The flow system is not simply through fractures or through matrix but is a continuum of flow paths that can involve both pores (of all sizes) and fractures (of all scales) and their connections. Thus, one should talk about a continuum (distribution) of flow paths.

through the CHn that bypass these highly sorptive minerals, however, retardation may not be as effective as it is for flow through the rock matrix.

C. Neptunium Solubility

The solubility[9] of Np is important because the isotope ^{237}Np is a major contributor to the calculated radiation dose at times of 10,000 years and beyond. The initial concentration of ^{237}Np (with a half life of 2.14×10^6 years) in spent nuclear fuel is approximately 0.03 percent. The concentration increases with time as ^{237}Np is produced by the decay of americium-241 (with a half life of 432 years).

The solubility-limited concentrations of Np were reevaluated recently (CRWMS 1998). The reevaluation concluded that the earlier (TSPA-95) solubility estimates (CRWMS 1995b) were based on experiments that used highly supersaturated solutions and that the resulting solubilities of Np were too high. In contrast, the recent reevaluation utilized experimental data for undersaturated systems, in which Np-bearing nuclear fuel was allowed to dissolve in water and to approach equilibrium from a state of undersaturation. As part of the reevaluation, thermodynamic calculations of the solubility of Np also were conducted. The authors of the reevaluation contend that the estimates of solubility from undersaturation represent a more realistic model of the situation that will exist in the proposed Yucca Mountain repository.

As a result of the reevaluation of experimental data, supported by thermodynamic calculations, the expected value for the solubility of Np has been lowered by approximately two orders of magnitude from that used in TSPA-95.[10] The new solubility values substantially lower the calculated long-term dose due to Np.

Despite the substantial effort that has gone into the reevaluation of the solubility data for Np, at least three important questions remain to be answered. First, does the new evaluation use the proper conceptual model? Second, has the role of secondary mineral precipitates been evaluated adequately? Third, have the starting Np-bearing solid phases in the SNF been characterized adequately? Each question is discussed below.

Regarding the first question, the recent reevaluation of the experimental data, as well as the computer simulations, assumes that the Np-bearing SNF dissolves in a water-saturated system. In other words, the use of data from a state of undersaturation assumes that the SNF will dissolve directly into water that will then move out of the repository and that the primary Np-bearing solid phases in the SNF will control the solubility of Np in the migrating water.

A different conceptual model would assume that the primary Np-bearing solid phases dissolve into water in a partially saturated system and that secondary Np-bearing minerals then precipitate from that water, possibly to be dissolved and remobilized at a later time. The secondary minerals could precipitate on or within the waste package itself, on or within the backfill material (if present), or within the fractures and matrix of the volcanic tuff that constitutes the repository host rock. If this conceptual model is more accurate, then the solubility of Np in subsequent flushes of water that may come through the repository will be controlled by the secondary Np-bearing mineral precipitates, not by the primary solids in the SNF. Secondary mineral precipitates can be more or less soluble than the primary solids from which they are derived and the calculated dose due to Np per unit of water could, as a result, be higher or lower. This alternative conceptual model would require the solubilities of the secondary mineral precipitates of Np to be evaluated.

The second question concerns the identity and solubility of possible secondary mineral precipitates of Np. If such compounds control the solubility of Np in water that may subsequently move through the

9. "Solubility" means the maximum amount of a material (in this case, neptunium) that can be dissolved in a unit amount of water.

10. The new expected value is $\log_{10}$(Np) (in mol/L) ~ -5.85, instead of the value of $\log_{10}$(Np) ~ -3.85 that was used in TSPA-95. The new $\log_{10}$ minimum and maximum values are -7.30 to -4.0 (in mol/L), compared with $\log_{10}$ of -5.30 to -2.0 in TSPA-95.

repository, then it is important to identify and characterize the secondary Np-bearing precipitates and to evaluate their solubilities.

The third question concerns the characterization and identification of the primary Np-bearing solids in the SNF. The recent reevaluation of the solubility of Np assumes that the controlling solid form in the SNF is NpO_2. However, nonstoichiometric forms of Np-oxygen compounds also may exist in the SNF, and they conceivably could control the solubility of Np. Metallic forms of Np, rather than NpO_2, may exist in the SNF, and such phases also may exert some control over the solubility of the Np. This possibility should be evaluated before a final solubility value is selected.

In conclusion, the remaining questions about the conceptual model and the occurrence and characteristics of the Np-bearing solid phases introduce significant uncertainty into the selection of the expected value of the solubility of Np. In light of this uncertainty, carrying a range of uncertainty about Np solubility of at least five orders of magnitude would be prudent.

VI. Influence of Climate Change

The climate of Yucca Mountain is now drier than the long-term average. During drier climates, the percolation flux is lower than normal, allowing a larger fraction of water to flow through the rock matrix than through the fractures. Radionuclides moving in the fractures can (1) enter the matrix as water imbibes into the matrix because of capillary forces (fracture-matrix interaction) or (2) diffuse into the rock matrix (matrix diffusion) and then travel at the slower velocities that occur in the matrix. These interactions can considerably lengthen radionuclide travel times through the UZ. Retardation also is assumed to be more effective in the rock matrix than in the fractures. Thus, radionuclide transport and the computed dose at the accessible environment will depend on the efficiency of the processes that transfer radionuclides from fractures into the matrix. Although these processes may be significant, no data on them are yet available for the UZ at Yucca Mountain.

A higher percolation flux is expected at Yucca Mountain when the climate returns to the long-term average or when it reaches superpluvial (much wetter and cooler) conditions. The conceptual model of flow in the UZ implies that as the percolation flux increases, a progressively larger fraction of flow will take place through fractures. Matrix diffusion and retardation of radionuclides may be reduced, allowing any radionuclides released from a Yucca Mountain repository to be transported more rapidly through the UZ toward the environment. Increased precipitation also will lead to a rise in the water table and a reactivation of paleo-groundwater discharge sites. The increase in percolation flux due to an increase in precipitation can be estimated through the data and associated models alluded to earlier (Flint, Hevesi, and Flint 1996). Therefore, the consequences of climate change can be estimated in TSPA by assumed increases in the percolation flux in the UZ, possible reductions in radionuclide retardation, a rise in the water table, and an increase in water flux in the SZ.

The DOE's base-case analysis for TSPA-VA considers three climate states: current dry state, with average precipitation of 170 mm / yr and average infiltration[11] of 7 mm / yr; long-term average climate (similar to Santa Fe and occurring ~80 percent of the time), with average precipitation of 300 mm / yr and average infiltration of 40 mm / yr; and superpluvial state (similar to Los Alamos) characterized by average precipitation of 450 mm / yr and average infiltration of 120 mm / yr. Because of the large uncertainties in these estimates, the infiltration flux is assumed to have a range of values around the assumed averages, i.e., infiltration ranges from one-third the average to three times the average. The timing of the climate

11. The percolation flux at the repository horizon, as calculated by the mountain-scale UZ flow model, is nearly the same as the near-surface infiltration flux.

states also has a large degree of uncertainty. The importance of this uncertainty is not clear and depends strongly on features of the EBS.

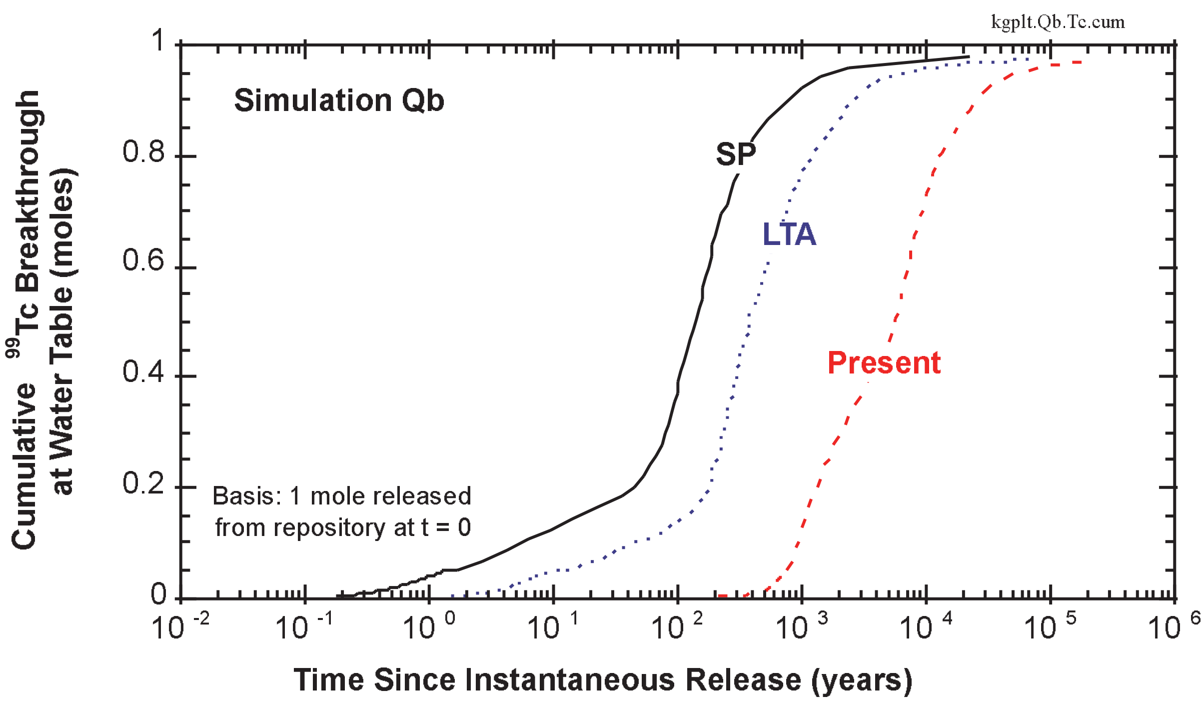
VII. Travel Times Through UZ

Because of their mineralogic and hydrologic properties, the CHn and the lower part of the overlying TSw unit are considered the principal UZ barriers to radionuclide migration. The Calico Hills formation consists of nonwelded unsaturated tuffs that contain a substantial proportion of zeolites. One of the important zeolite minerals, clinoptilolite, is responsible for strong-to-moderate adsorption of key radionuclides, such as ^{237}Np. The CHn also is substantially less fractured than the overlying repository horizon (TSw).

For quantifying the hydrologic and transport properties of the CHn and the role it could play as a natural barrier, field tests are being carried out at the Busted Butte site, an exposure of the CHn south of Yucca Mountain. The Busted Butte locality provides access to both vitric and zeolitic parts of the CHn formation, as well as the lower part of the TSw, and is analogous to the UZ barrier beneath the potential repository at Yucca Mountain. In situ large-scale field tests, including conservative and reactive tracers, will address the flow-and-transport properties in this unsaturated unit. The response of this unit to different degrees of water saturation and to the species of transported materials will be of special interest.

Figure 2-2 shows the travel times through the UZ for nonsorbing technetium as presently modeled in TSPA-VA (Andrews 1998b). The three curves represent the computed breakthrough curves at the water table (i.e., distribution of travel times through the UZ) for unretarded radionuclides for the three climate states assumed in TSPA-VA. Although most of the flow takes place through the fractures for the long-term average and the superpluvial climates, diffusion of the radionuclides into the matrix reduces the fraction of radionuclides transported solely through fractures to approximately 20 to 30 percent. The other 70 to 80 percent of radionuclides will diffuse into and out of water that flows much

Figure 2-2. Breakthrough Curves for Superpluvial (SP), Long-Term Average (LTA), and Present Climates (Andrews 1998b).



more slowly through the matrix of the rock. Thus, even though most of the flow occurs in fractures, most radionuclides will be retarded to some degree.

In Figure 2-2, the distributions of travel times from the repository to the assumed level of the water table can include some very rapid values. For example, 50 percent of radionuclide travel times are predicted to be several hundred years or shorter during superpluvial conditions. The travel-time distribution through the UZ has not been quantified through direct measurements. It is highly model-dependent and yet is significant for performance. Although very fast travel times through the UZ exist (e.g., bomb-pulse ^{36}Cl discovery in the ESF), these times might represent only a very small fraction of flow. The uncertainties remain large, and the significance of the UZ as a barrier is uncertain.

It is important to determine the extent to which the breakthrough curve of Figure 2-2 may be an artifact of the way transport through the UZ is modeled. Travel times through the natural barriers represent an important component of a defense-in-depth repository design, especially in case of premature canister failure. Current TSPA models (e.g., base case for VA) assume that a fraction of the flow takes place through fractures and that this component of flow leads to fast travel times through the UZ. These models may not adequately represent the physics of flow within the fractured rocks of the UZ at Yucca Mountain. More data and better models are needed to demonstrate whether radionuclide travel times through the UZ could be significant (thousands of years), allowing the UZ to serve as a substantive natural component of a multiple-barrier repository design.

VIII. Colloids

Field studies have shown that strongly sorbing radionuclides, such as plutonium, may sorb on naturally occurring colloids[12] in groundwater and migrate at velocities similar to the velocity of groundwater flow. This process can lead to travel distances of radionuclides that are far greater than those predicted by retardation factors measured in laboratory experiments. Recently, plutonium was measured in groundwater at the Nevada Test Site ER-20-5 wells at a maximum level of 0.63 pCi/l (Kersting et. al 1997). The plutonium origin was the nuclear test BENHAM on Pahute Mesa, 1.3 km north of the ER-20-5 location, at a depth of 1,402m (4,599 ft), which is well below the static water table at 641 m (2,102 ft). All of the plutonium detected was associated with colloidal components, primarily clays and zeolites.

This observation and other laboratory experiments indicate that colloidal transport cannot be ignored and can contribute to the transport of strongly sorbing radionuclides, potentially increasing the dose at the accessible environment. Key data, such as the reversibility of sorption on colloids and colloid stability are required to estimate or bound the importance of colloidal transport. Some of the testing at Busted Butte is being conducted to assess the transport of colloids through the unsaturated CHn and should provide enough information to reduce uncertainty about colloid transport.

IX. Conclusions

The UZ of Yucca Mountain is potentially an important component of a defense-in-depth repository design. The following are the Board's conclusions about the current state of knowledge of the UZ.

- The effects of repository heat on thermohydrologic conditions near the repository are not well understood, but tests have been initiated at Yucca Mountain to improve understanding and reduce uncertainties.

- Seepage flux under ambient conditions can be better estimated through the proposed in situ experiments, by analog studies at the Nevada Test Site, and by numerical simulations. Seepage after the thermal period has not been addressed in the past,

12. A colloid is a particle that can be suspended easily or is a suspension of very fine particles.

but planned experiments may produce relevant data. To the Board's knowledge, the effects of near-field changes (e.g., tunnel collapse) are not being addressed.

- Despite recent progress in reevaluating the solubility of Np, significant uncertainties (possibly as much as five orders of magnitude) remain. Because the long-range dose potential of ^{237}Np is so significant, additional efforts are needed to narrow these large uncertainties.

- More data and better models are needed to demonstrate whether radionuclide travel times through the UZ could be significant (thousands of years), allowing the UZ to serve as a substantive natural component of a multiple-barrier repository design.

- The testing at Busted Butte is being conducted to assess the transport of colloids and other aqueous species through the UZ below the repository and should provide enough information to reduce uncertainty.