U.S. NUCLEAR WASTE TECHNICAL
REVIEW BOARD

Report to
The U.S. Congress
And
The U.S. Secretary of Energy

November 1998

Additional copies of this report and previous NWTRB reports are available from the Board's office:
NWTRB, 2300 Clarendon Boulevard, Suite 1300, Arlington, VA 22201-3367.
All NWTRB reports also are available at **www.nwtrb.gov**, the NWTRB Web site.

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3367

November 1998

The Honorable Newt Gingrich
Speaker of the House
United States House of Representatives
Washington, DC 20515

The Honorable Strom Thurmond
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable Bill Richardson
Secretary
U.S. Department of Energy
Washington, DC 20585

Dear Speaker Gingrich, Senator Thurmond, and Secretary Richardson:

The Nuclear Waste Technical Review Board (Board) submits this report in accordance with the requirements of the Nuclear Waste Policy Amendments Act of 1987, Public Law 100-203.

Congress created the Board to evaluate the technical and scientific validity of activities undertaken by the Department of Energy (DOE) for disposing of the nation's spent nuclear fuel and high-level radioactive waste, including the DOE's program for characterizing a proposed repository site at Yucca Mountain in Nevada. The Board also reviews DOE activities related to packaging and transporting spent fuel and high-level waste.

In its report, the Board evaluates information about the proposed repository system, with emphasis on the unsaturated zone, the engineered barrier system, and the saturated zone. The Board considers some of the important connections between the site's natural properties and the current designs for the waste package and other engineered features of the repository. The Board also comments on research, much of which is already under way or planned, that will be needed to support important program milestones, including determining whether the site is suitable and licensing the repository, if the determination is positive. We believe that the information in this report will be useful to policy makers and DOE managers, staff, and contractors.

The Board emphasizes that this report is *not* a review of the forthcoming viability assessment (VA) of the site. The Board plans to comment on the technical and scientific aspects of the VA after it is issued by the DOE.

Telephone: 703-235-4473 Fax: 703-235-4495

We thank you for the opportunity to serve the Congress, the Department of Energy, and the nation. We share and are committed to the common goal of furthering safe and cost-effective management of spent nuclear fuel and high-level radioactive waste.

On behalf of the Board,

Jared L. Cohon
Chairman

NUCLEAR WASTE TECHNICAL REVIEW BOARD

Executive Staff

William D. Barnard	*Executive Director*
Michael G. Carroll	*Deputy Executive Director*

Technical Staff

Carlos A.W. Di Bella	*Senior Professional Staff*
Daniel J. Fehringer	*Senior Professional Staff*
Russell K. McFarland	*Senior Professional Staff*
Daniel S. Metlay	*Senior Professional Staff*
Victor V. Palciauskas	*Senior Professional Staff*
Leon Reiter	*Senior Professional Staff*

External Affairs Staff

Karyn D. Severson	*Director*
Paula N. Alford	*Consultant*

Publications Staff

Ayako O. Kurihara	*Editor*
William D. Harrison	*Production Consultant*

Administrative & Support Staff

Davonya S. Barnes	*Staff Assistant*
Linda Coultry	*Staff Assistant*
Debra K. Hairston	*Management Assistant*
Linda L. Hiatt	*Management Assistant*
Victoria F. Reich	*Librarian*

Table of Contents

List of Figures

Executive Summary

The U.S. Nuclear Waste Technical Review Board evaluates the technical and scientific validity of activities undertaken by the Secretary of Energy to characterize Yucca Mountain in Nevada for its suitability as a location for a repository for high-level radioactive waste (HLW) and spent nuclear fuel (SNF). The U.S. Department of Energy (DOE) plans to complete a "viability assessment" (VA) of the Yucca Mountain site in the fall of 1998. Then, under the current schedule, the DOE will advise the President in 2001 on whether the site is suitable for developing a repository. If the President accepts a positive recommendation, the DOE intends to apply to the Nuclear Regulatory Commission (NRC) in 2002 for a license authorizing repository construction.

The DOE has made considerable progress in characterizing the Yucca Mountain site and developing a comprehensible waste isolation strategy for a repository that might be located there. Plans are being made for new and continuing scientific and technical work that will be conducted following the VA to help reduce some key uncertainties. In general, the Board believes that the DOE has identified some of the key areas of research whose results would improve the technical basis for making a determination about site suitability and, if appropriate, for applying to the NRC for a license to build a repository. The Board offers its views in this report about the objectives and priorities of future research for supporting these milestones. The Board emphasizes that this report is *not* a review of the forthcoming VA. The Board intends to offer its views on the technical and scientific aspects of the VA in a timely manner after the VA is issued.

The Board realizes that at the time a decision on site suitability is made, not all uncertainties about the proposed Yucca Mountain repository will have been resolved fully. The question of how much scientific uncertainty is tolerable at the time of a suitability determination for the Yucca Mountain site is ultimately a policy question. The Board believes that its role is to identify current uncertainties associated with the overall performance of the repository system and its constituent parts, describe the technical and scientific means by which some of those uncertainties could be reduced, and estimate the approximate time at which the scientific results might be available.

The Board strongly supports continuing focused studies of both the natural and the engineered barriers at Yucca Mountain to attain a defense-in-depth repository design and to increase confidence in predictions of potential health effects in the future. Although there are economic and technical limits to reducing uncertainties, the Board believes that some key uncertainties could be further reduced over the next several years through a focused research effort. One line of work is to continue investigating alternative repository and waste package designs that could reduce the level of uncertainty about the performance of the overall repository system. Another is testing some of the important hypotheses about waste package materials under well-controlled conditions.

In this report, the Board evaluates information about the proposed repository system presented to it in meetings and other exchanges, with emphasis on the unsaturated zone (UZ), the engineered barrier system (EBS), and the saturated zone (SZ). The Board considers and comments on some of the important connections between the site's natural properties and the current designs for the waste package and the other engineered features of the repository.

The UZ at Yucca Mountain is a critical natural feature of the repository system because it would form the roof, foundation, and interior of the repository itself. Along with structural integrity, the UZ would provide the hydrologic and chemical environment for the waste packages and would be the first natural medium through which the radionuclides, when released, would be transported by water to the SZ. The volume and geochemistry of the water that may reach waste packages, cause them to corrode, mobilize the waste, and carry radionuclides to the water table are key parameters affecting the long-term isolation of radioactive waste in a Yucca Mountain repository.

The present level of uncertainty about seepage (water entering repository tunnels) is high. Experiments that are under way have the potential to reduce this uncertainty over the next several years. Ongoing observations of bomb-pulse chlorine-36 and other isotopes at the repository horizon and at comparable settings nearby must continue to be collected and analyzed systematically. Data from experiments in the single-heater and drift-scale heater tests should provide insights into moisture movement during above-boiling thermal conditions, thus reducing thermohydrologic uncertainties. Experiments under way at Busted Butte will characterize better the transport of radionuclides in the UZ after their release from waste packages. Data from these studies will enhance confidence in conceptual models of groundwater flow and radionuclide transport in the UZ of Yucca Mountain.

Many aspects of repository design may affect waste isolation, including tunnel diameter, tunnel stability, waste emplacement mode, and use of backfill or drip shields. The EBS would play a key role in isolating radioactive waste in a Yucca Mountain repository, especially if a highly corrosion-resistant waste package material (e.g., a nickel-base alloy) is used. The DOE intends to evaluate alternative features and design concepts that may enhance performance or decrease uncertainty. Among the more important alternatives to be evaluated are lower-temperature designs that use ventilation to reduce uncertainties about the heat-induced hydrologic, mechanical, and chemical changes in the rock surrounding waste emplacement tunnels. Observations and experimental results from the Exploratory Studies Facility and the recently completed cross drift above the repository horizon may increase confidence in predictions of tunnel stability and short- and long-term performance.

Research is under way for assessing and placing bounds on corrosion rates of candidate waste package materials for repository conditions. Continuing this research is vital. Also important is continued development of waste package manufacturing methods, including quality control, inspection, and postweld heat treatment, all of which are essential for preventing early failures and extending waste package life. Long-term research will be needed to detect and control or mitigate any processes that could damage the passive layer that forms on the surface of a corrosion-resistant waste package metal and greatly retards further corrosion of the metal. In addition, the long-term phase stability of nickel-base alloys needs to be studied to identify the effects of possible phase instability on corrosion resistance.

The SZ may act as a natural barrier by (1) delaying the arrival of radionuclides at the accessible environment and (2) reducing radionuclide concentrations in groundwater, and thus dose to a critical group, through dispersion and dilution. The SZ may have a greater potential as a barrier than can be demonstrated by currently available data. The Board believes that continued single- and multiple-well testing of the type conducted at the C-well complex is necessary to bound estimates of flow-and-transport parameters on the basis of field observations. The Board also believes that continued geochemical characterization of the water in the SZ is important. Parts of the SZ may be a chemically reducing environment in which oxygen is absent. If so, some of the very-long-lived radionuclides that are sensitive to the oxidizing or reducing potential of the groundwater, including neptunium and uranium, would precipitate, permanently removing them from the groundwater and reducing predicted radiation doses at the biosphere.

The Nye County drilling project envisions 21 wells, some shallow and some deep. The drilling project, in conjunction with the proposed U.S. Geological Survey testing program, should provide data on the three-dimensional characteristics of the regional flow system and the geochemical character of water near the tuff-alluvium interface. The flow-and-transport model should be revised as data from these new and continuing site-characterization efforts become available.

The current repository design for Yucca Mountain envisions "defense-in-depth" that is provided by both natural and engineered barriers. Uncertainties remain about the long-term performance of each barrier, and additional studies are needed, as discussed in this report. The Board strongly supports continuing focused studies of both the natural and the engineered barriers at Yucca Mountain to attain a defense-in-depth repository design and to increase confidence in predictions of potential health effects in the future.

Chapter 1

Overview

The U.S. Nuclear Waste Technical Review Board evaluates the technical and scientific validity of activities undertaken by the Secretary of Energy to characterize Yucca Mountain in Nevada for its suitability as a location for a repository for high-level radioactive waste (HLW) and spent nuclear fuel (SNF). The U.S. Department of Energy (DOE) began studying Yucca Mountain as a potential repository site in 1983. The efforts intensified in the early 1990's.

Several attractive natural features of Yucca Mountain led to its selection as a potential repository site:

- Yucca Mountain now receives relatively little precipitation.
- Only a small part of the rain falling or the snow melting on Yucca Mountain percolates deep into the rock above the water table.
- Water percolating downward into the mountain generally moves very slowly.
- The site is owned by the federal government and currently is uninhabited.

The DOE plans to complete a "viability assessment" (VA) of the site in the fall of 1998.[1] Then, under the current schedule, the DOE will advise the President in 2001 on whether the Yucca Mountain site is suitable for developing a repository. If the President accepts a positive recommendation, the DOE intends to apply to the Nuclear Regulatory Commission (NRC) in 2002 for a license authorizing repository construction.

In this report, the Board evaluates information about the proposed repository presented to it in meetings and other exchanges, with emphasis on the unsaturated zone[2] (UZ), the engineered barrier system[3] (EBS), and the saturated zone[4] (SZ). The Board considers and comments on some of the important connections between the site's natural properties and the current designs for the waste package and the other engineered features of the repository. The Board's comments reflect its understanding of the program's status and plans. There may be aspects of the program on which the Board has not been briefed or with which the Board has not had the opportunity to become familiar.

---

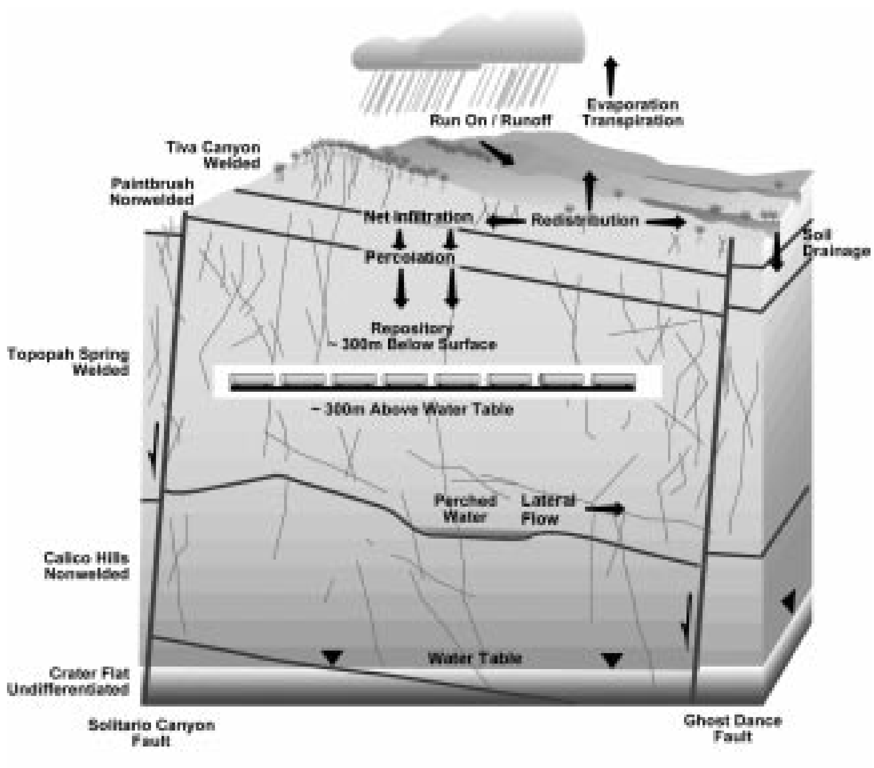
[1] The Energy and Water Development Appropriations Act for Fiscal Year 1997 (U.S. Congress 1996) requires the DOE to produce the VA. It will consist of four parts: (1) a preliminary design concept for critical elements of the waste package and of the engineered part of a repository at Yucca Mountain; (2) an evaluation of the probable behavior of the repository that is based on available data; (3) a plan and a cost estimate for completing the application for constructing the repository; and (4) a cost estimate for constructing and operating the repository. The VA will not address issues associated with the transport of SNF and HLW.

[2] The unsaturated zone consists of geologic formations located above the regional groundwater table.

[3] The engineered barrier system consists of the waste packages, emplacement tunnels, backfill, and any other engineered components of a disposal system designed to slow down or prevent the release of radionuclides from the repository.

[4] The saturated zone is the part of the earth's crust in which all voids are filled with water under pressure at least as great as atmospheric pressure. The upper limit of the saturated zone is the water table.

Figure 1-1. Potential Repository System at Yucca Mountain (adapted from Andrews 1998b)



The DOE has made considerable progress in characterizing the Yucca Mountain site and developing a comprehensible waste isolation strategy for a repository that might be located there. However, uncertainties about the site and the performance of the proposed repository remain. Plans are being made for new and continuing scientific and technical work that will be conducted following the VA to help reduce some key uncertainties. In general, the Board believes that the DOE has identified some of the key areas of research whose results would improve the technical basis for making a determination about site suitability and, if appropriate, for applying to the NRC for a license to build a repository. The Board offers its views in this report about the objectives and priorities of future research for supporting these milestones. The Board emphasizes that this report is *not* a review of the forthcoming VA. The Board intends to offer its views on the technical and scientific aspects of the VA in a timely manner after the VA is issued.

The Board realizes that at the time a decision on site suitability is made, not all uncertainties about the proposed Yucca Mountain repository will have been resolved fully. The question of how much scientific uncertainty is tolerable at the time of a suitability determination for the Yucca Mountain site is ultimately a policy question. The Board believes that its role is to identify current uncertainties associated with the overall performance of the repository system and its constituent parts, describe the technical and scientific means by which some of those uncertainties could be reduced, and estimate the approximate time at which the scientific results might be available.

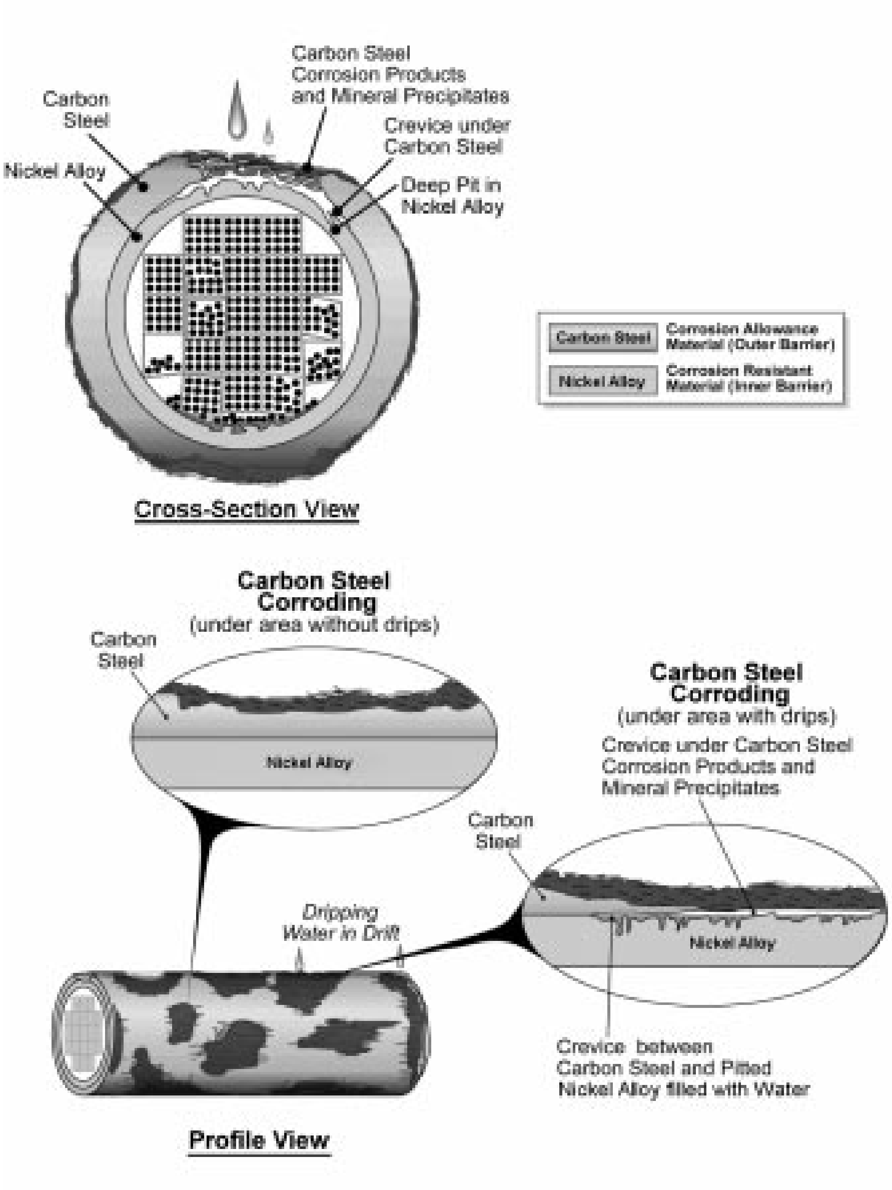
I. The Repository as a System

The proposed repository is a system of interacting engineered and natural geologic components. (Figure 1-1 shows the configuration of a potential repository system at Yucca Mountain.) Although the *concept* associated with waste isolation is not especially complex, predicting repository performance is challenging because of the inherent difficulty in precisely characterizing the typically complex geologic conditions at the site and the lack of data on the performance of engineered materials over the long period of concern (thousands of years). The most important consideration in evaluating the suitability of the Yucca Mountain site is the ability of a repository located there to isolate radioactive wastes from the human environment. This ability to isolate waste is called "performance of the overall repository system."

A repository design that includes multiple indpendent natural and engineered barriers is said to offer "defense-in-depth," a concept strongly endorsed by the Board (Cohon 1997). The confidence placed in various barriers at a Yucca Mountain repository may change over time as more information is acquired about the characteristics of the engineered and natural components and their interactions.

Scientists have developed a conceptual model of how a repository at Yucca Mountain might isolate nuclear waste for thousands of years. At Yucca Mountain, the water table is about 600 meters below the surface, allowing wastes to be placed about 300 meters above the water table in the UZ. Although the part of Yucca Mountain proposed for repository construction is unsaturated, some water moves downward through it and may contact waste packages, causing them to corrode over long periods of time. Eventually, corrosion would penetrate the walls of some waste packages, allowing water to enter and slowly begin dissolving the waste. (Figure 1-2 shows waste package degradation as depicted by the DOE's management and operating [M&O] contractor.) Even then, the postulate is that only small amounts of radionuclides would seep down through the floors of emplacement tunnels, because the volume of water available to transport the material would be small relative to the amount of water in other geologic environments.

Figure 1-2. Waste Package Degradation (adapted from Andrews 1998b)



Any water leaving the repository would have to transport the released waste material downward about 300 meters through the remaining part of the UZ before reaching the water table. During movement through the UZ below the repository, the water will encounter minerals, including zeolites, that could adsorb many of the components from the waste, delaying or entirely preventing their movement to the water table. However, much of the flow of water through the UZ may occur in rock fractures. If so, adsorption would be much less effective in delaying movement of radionuclides.

Hundreds, perhaps thousands, of years after the packages have been breached, the fraction of the waste that has been mobilized would reach the water table, where it would be diluted and dispersed to some degree. Now mixed with a larger volume of groundwater, the mobilized components would be transported down the groundwater gradient (in the direction of Amargosa Valley), where they would either remain below the earth's surface or enter the biosphere through withdrawals from water wells or through natural discharges in springs and seeps.

At the proposed Yucca Mountain repository, wastes would be placed in tunnels excavated in tuff (solidified volcanic ash) about 300 meters below the land surface and about 300 meters above the regional water table. In this UZ, under present climatic conditions, there generally would be little, if any, water dripping into tunnels. However, water may enter the repository episodically, especially after intense rainstorms or heavy snowfalls.[5] This water is a major factor that determines how the repository components interact with each other, as well as how effectively the overall repository system can isolate waste from the environment. Among the interactions of concern are the following:

- *Water and Waste Package Environment.* The amount and chemical composition of water entering the repository and the time at which it contacts waste packages affect the rate at which waste packages will corrode and, eventually, the rate at which water can carry wastes away from the repository. Therefore, features of the repository that can reliably minimize seepage and contact of waste packages with water are desirable.

- *Tunnel Stability and Waste Package Environment.* Rockfalls or collapse of tunnels could physically damage waste packages, alter the locations or the rates at which water enters the repository, and affect the flow of air and the dissipation of heat.

- *Thermal Loading.* Radioactive decay of wastes generates heat, which would have pervasive but uncertain effects throughout the repository, particularly during the first several centuries after waste emplacement. The layout of the repository, the extent of ventilation, and the mix of waste packages all affect the "thermal loading," or extent of heating, in the repository. Above-boiling temperatures affect water flow through the UZ in ways that are complex and difficult to predict.[6] Heat also affects chemical reactions, including those that influence the waste package environment and the rate of waste package corrosion. Expansion of rocks as they heat up and contraction later as they cool down may affect tunnel stability and hydrologic properties.

The repository system also may be influenced by changes in outside (boundary) conditions. For example, during the next several thousand years, the climate at Yucca Mountain is expected to become cooler and wetter. Increased precipitation could substantially increase the amount of water penetrating to repository depth, which in turn could affect repository performance.

A repository should be designed to reduce the importance of potentially negative interactions among some of its components. For example, smaller-diameter tunnels would be more stable than larger-diameter tunnels, reducing uncertainty about the effects of rockfalls on the waste package environment. Another example is the thermal loading of the repository. If the temperature rise can be limited (e.g., by ventilation, through aging of wastes, or by other means), there would be less disturbance of the hydrologic, mechanical, and chemical conditions in rocks surrounding the repository tunnels. The objective of changing the repository design from its current configuration would be to create a more predictable and less corrosive environment for the waste package.

---

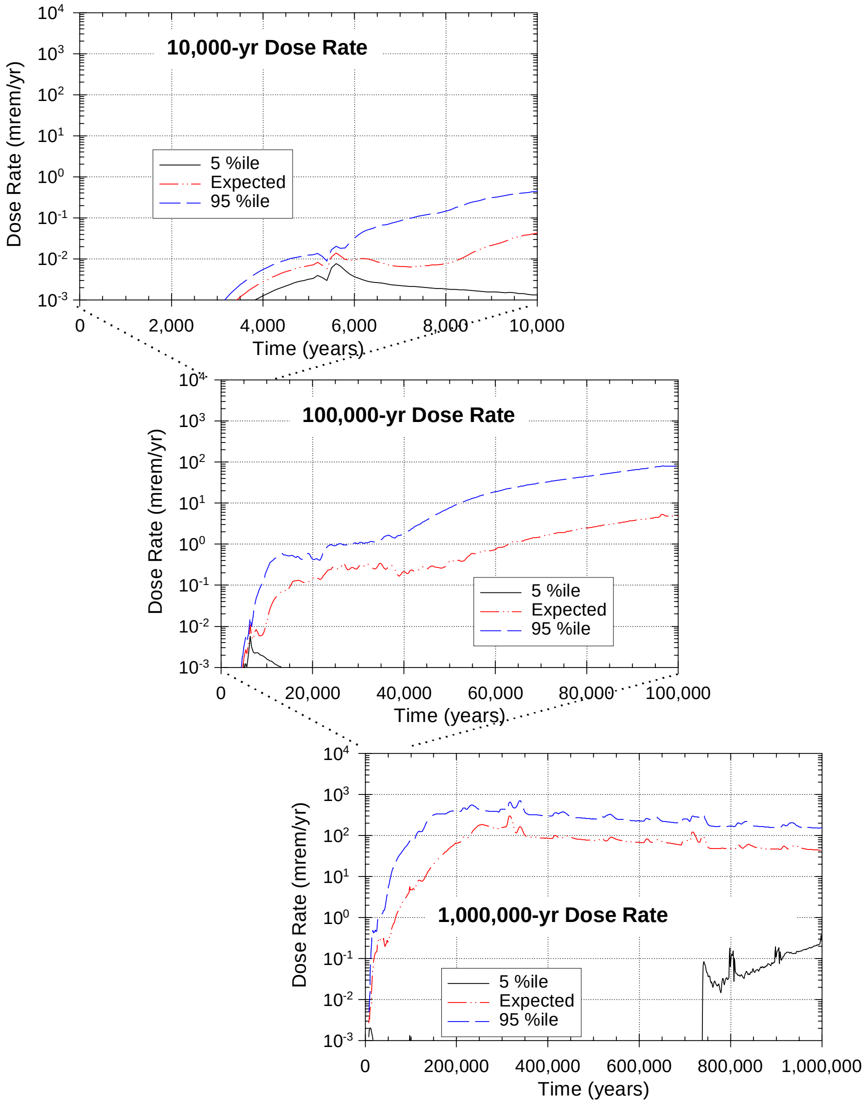
[5] The amount of precipitation at the surface of Yucca Mountain that could cause water to enter tunnels at repository depth is unknown.

[6] Ideally, heat could prevent any water from entering the repository in liquid form for as long as several thousand years, as discussed in the chapter on the engineered barrier system in this report.

II. Features Affecting Repository Performance

The Board's evaluation of the major features likely to affect performance of a repository system at Yucca Mountain and its evaluation of the major sources of uncertainty in projections of performance are presented in the next three chapters of this report. Key observations and conclusions are summarized below.

Figure 1-3. Estimated Sensitivity of Dose Rate to Unsaturated Zone Seepage (Andrews 1998b)



A. Unsaturated Zone[7]

The UZ at Yucca Mountain is a critical natural feature of the repository system because it would form the roof, foundation, and interior of the repository itself. Along with structural integrity, the UZ would provide the hydrologic and chemical environment for the waste packages and would be the first natural medium through which the radionuclides, when released, would be transported by water to the SZ.

The volume and geochemistry of the water that may reach waste packages, cause them to corrode, mobilize the waste, and carry radionuclides to the water table are key parameters affecting the long-term isolation of radioactive waste in a Yucca Mountain repository. For example, Figure 1-3 illustrates the relationship between the assumed variation in the amount of water seeping into repository tunnels and the radiation doses predicted in the DOE's performance assessments for a Yucca Mountain repository. Seepage of water into repository tunnels is determined by the amount of water that infiltrates into the mountain and penetrates to repository depth and by the fraction of that water that is assumed to enter tunnels rather than staying within the rocks and flowing around the tunnels. The DOE's assumptions about these parameters allow calculation of a range of values for the seepage flux,[8] characterized by the 5th, expected (50th), and 95th

---

[7] See Chapter 2 for details.

[8] Other assumptions about input parameters could lead to wider or narrower ranges of estimated dose rates.

percentiles. The 5th percentile represents parameter values that result in low seepage, and therefore low dose rates; the 95th percentile shows how parameter values that cause higher seepage also cause higher doses. Dose rates over time for the 5th, 50th, and 95th percentiles of the seepage flux are illustrated in Figure 1-3.

Current understanding of the spatial distribution of water-transmitting properties of the UZ in the area above the repository is described by a map of surface infiltration, which is based on a model derived from extensive field observations (Flint 1995). Water that permanently infiltrates the mountain is delayed and spatially redistributed by the underlying heterogeneous rock strata, but it eventually percolates down to the repository horizon. Because making direct measurements of the percolation flux deeper inside the mountain is impractical, the *assumption* is that the net infiltration flux (the spatial and temporal average) above the repository "footprint" is equal to the average flux of water reaching the repository horizon. No lateral diversion of water is assumed.[9]

Detailed spatial and temporal characterization of water flow in the UZ is neither possible nor necessary at Yucca Mountain. Rather, statistically quantifying the anticipated timing and distribution of water flow and how this natural variability affects the probable performance of the repository system is sufficient. Additional data will be needed to develop a statistical description of the UZ hydrologic conditions at Yucca Mountain, but those data need not be as extensive as would be required for a complete characterization of the mountain.

1. Key UZ Uncertainties

A fraction of the percolating water may seep into the emplacement tunnels, causing waste packages to corrode and, after hundreds or thousands of years, contacting the waste form and removing radionuclides from the EBS. The magnitude and distribution of this seepage are major uncertainties that contribute to uncertainty about repository performance.

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. If the repository is designed for above-boiling temperatures, there may be additional water movement around, and perhaps into, the emplacement tunnels when temperatures are high. The rocks of the repository horizon, although not fully saturated, contain a significant volume of water. As temperatures in the host rock rise above the boiling point, this water will be vaporized in the rock pores and move within fractures toward cooler, below-boiling regions. There, the vapor will condense and migrate downward from the point of condensation. The consequences of this complex, transient, and episodic hydrologic process are difficult to predict, resulting in significant uncertainty about the environment for the waste packages.

Geochemical conditions in the UZ also may be important for projecting repository performance. For example, neptunium (Np) is a critical radionuclide affecting the estimated peak radiation dose at longer times (after 10,000 years). Both the solubility of Np and its retardation during transport through the UZ are uncertain at present. Consequently, there is a large uncertainty about the size of the computed peak dose and its timing. 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.

Although plutonium is a strongly sorbing element, it may migrate significant distances by colloidal transport, resulting in additional uncertainty about predicted radiation doses. The potential for colloids to form and enhance transport of radionuclides in the UZ at Yucca Mountain is poorly understood at present.

---

[9] The Paintbrush tuff above the repository horizon has the potential to act as an "umbrella," diverting some infiltrating water from the repository. Recent information suggests that fractures in the Paintbrush tuff allow downward water flow, so lateral diversion is now assumed not to occur.

2. Addressing Key UZ Uncertainties

The present level of uncertainty about seepage flux is high. In 1997, the DOE completed construction of a 5-mile-long tunnel, the Exploratory Studies Facility (ESF), located in the UZ immediately east of the proposed repository area. Scientists have been collecting valuable data from the ESF since its construction began in 1995. In addition, experiments that are under way have the potential to reduce this uncertainty over the next several years. Ongoing observations of bomb-pulse chlorine-36 (^{36}Cl) and other isotopes at the repository horizon and at comparable settings nearby must continue to be collected and analyzed systematically. These data will enhance our confidence in conceptual models of flow in the UZ.

Data from experiments in the single-heater and drift-scale heater tests should provide insights into moisture movement during above-boiling thermal conditions, thus reducing thermohydrologic uncertainties. The single-heater test has been completed and has provided useful information on the movement of water, showing that mobilized water drained around the heated rock and a dryout region formed. The drift-scale test that began on December 6, 1997, is designed to provide similar data but on a much larger scale and for a much longer time. (The total duration of the heater experiment will be about 8 years.)

Experiments under way at Busted Butte will characterize better the transport of radionuclides in the UZ after their release from waste packages. Specifically, these experiments are designed to investigate the transport properties of reactive and nonreactive tracers in the lower part of the repository horizon and in the vitric tuffs of the Calico Hills formation underlying the repository horizon. Special emphasis will be on the retardation potential of the vitric tuffs and the efficacy of colloidal transport through this unit. Data from these studies will enhance confidence in conceptual models of groundwater flow and radionuclide transport in the UZ of Yucca Mountain. These data should be available in 2 years.

B. Engineered Barrier System[10]

The EBS would play a key role in isolating radioactive waste in a Yucca Mountain repository, especially if a highly corrosion-resistant waste package material (e.g., a nickel-base alloy) is used. Many aspects of repository design may affect waste isolation, including tunnel diameter, tunnel stability, waste emplacement mode, and use of backfill or drip shields.

In the current reference design for a Yucca Mountain repository, the waste package is the component of the EBS that is the most important for isolating radioactive waste. The projected package performance depends primarily on the corrosion resistance of a 2-cm-thick wall of a nickel-base alloy, Alloy 22.[11] This relatively new alloy was selected for its potential to provide durability for very long periods. (Figure 1-4, on page 8, shows the sensitivity of dose rate to the assumed variation in the degradation rate of Alloy 22, as projected in recent performance assessments.) The alloy resists corrosion by forming a very thin layer (a passive layer) on its surface. As long as the passive layer remains intact, it acts as a barrier between the metal and its oxidizing environment, greatly reducing the rate of further corrosion.

1. Key EBS Uncertainties

Alternative repository and EBS designs could improve waste isolation or reduce uncertainties in projections of repository performance. A thorough evaluation of alternatives is needed.

Extrapolating corrosion behavior from the limited history of use of similar metals (decades) to predict waste package performance over a 10,000-year period is a source of uncertainty in the predicted performance. Uncertainties in predicting the corrosion rate of a nickel-base alloy primarily involve questions about the long-term stability of the passive layer.

---

[10] See Chapter 3 for details.

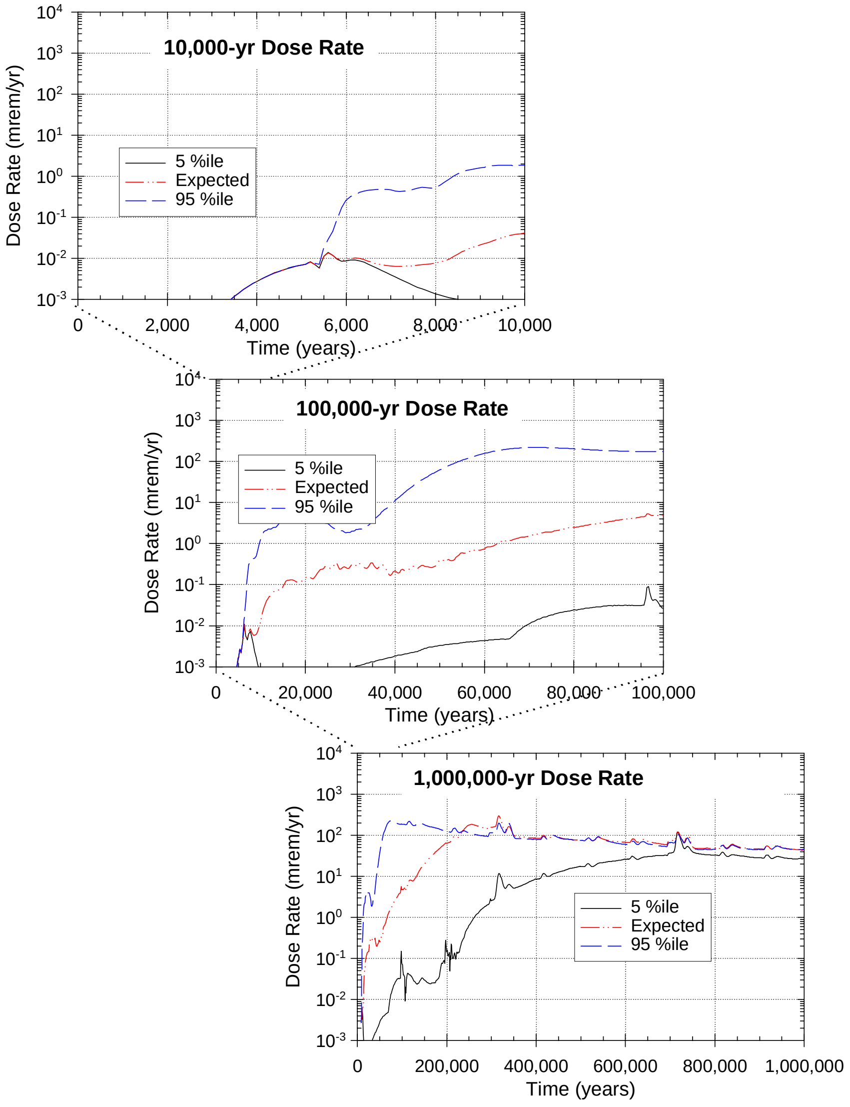
[11] ”Alloy 22” (UNS N06022) is a generic term for C-22, which is the trade name of a specific manufacturer.

2. Addressing Key EBS Uncertainties

Over the next several months, the DOE intends to evaluate alternative features and design concepts that may enhance performance or decrease uncertainty. Among the more important alternatives to be evaluated are lower-temperature designs that use ventilation to reduce uncertainties about the heat-induced hydrologic, mechanical, and chemical changes in the rock surrounding waste emplacement tunnels.

Criteria for evaluating alternative features and design concepts have not been clearly defined yet, and the schedule established by the DOE for their evaluation may be difficult to meet. The evaluation should be framed around the overall objective of reducing uncertainties in performance. It might include a reexamination of key self-imposed geologic constraints and design assumptions, including minimum thickness of rock cover, minimum offset from faults, minimum distance from zeolite-rich strata and from the water table, and selection of the substrata in which emplacement tunnels are to be located.

Figure 1-4. Estimated Sensitivity of Dose Rate to Degradation Rate of Alloy 22 (Andrews 1998b)



Research is under way for assessing and placing bounds on corrosion rates of candidate waste package materials for repository conditions. Continuing this research is vital. Also important is continued development of waste package manufacturing methods, including quality control, inspection, and postweld heat treatment, all of which are essential for preventing early failures and extending waste package life. Also needed is continued intensive examination of waste package alternatives that offer performance benefits: e.g., improved defense-in-depth in comparison to the current steel outer-wall and Alloy 22 inner-wall package design, including the possible use of titanium alloys instead of or in combination with nickel alloys.

Efforts should be made to assess the likelihood of failure by unknown modes of damage to the passive layer on corrosion-resistant waste package materials. These efforts should include examining human experience with long-term performance of artificial materials, examining the behavior of possible natural or archaeological analogs (e.g., meteorites, ancient alloys), and performing fundamental research focused on the processes or factors that may affect the long-term stability of the passive layer.

Long-term research will be needed to detect and control or mitigate any processes that could damage the passive layer that forms on the surface of a corrosion-resistant metal and greatly retards further corrosion of the metal. In addition, the long-term phase stability of nickel-base alloys needs to be studied to identify the effects of possible phase instability on corrosion resistance. The research will need to be complemented by periodic observation and sampling of waste packages that have been loaded with radioactive waste and emplaced in disposal locations. If a 10,000-year repository performance standard is adopted, the research, observation, and sampling could go on for half a century or more to develop high confidence. Activities must take place in environments that represent or bound the near-field tunnel environments that exist in the vicinity of the waste packages, including modifications to these environments due to interactions with corrosion products, rockfalls, concrete, dust, microbes, radiation effects, and dripping water.

Observations and experimental results from the ESF and the recently completed cross drift above the repository horizon may increase confidence in predictions of tunnel stability and short- and long-term performance. Analyses are needed to evaluate the stability of an unlined emplacement tunnel during and after thermal loading in each of the repository rock units, including possible deterioration of the rock mass.

C. Saturated Zone[12]

The SZ may act as a natural barrier by (1) delaying the arrival of radionuclides at the accessible environment and (2) reducing radionuclide concentrations in groundwater, and thus dose to a critical group, through dispersion and dilution. Figure 1-5, on page 10, shows the sensitivity of dose rate to assumed variation in the SZ dilution, as estimated in recent performance assessments.

Relatively little attention was paid to dilution in the SZ during early site-characterization efforts because regulatory criteria then were based on release rates from the EBS and on groundwater travel time from the repository to the accessible environment. Thus, potential dilution and chemical reactions in the SZ did not seem important. Regional groundwater was estimated to be old, supporting the concept of travel times longer than 10,000 years to the accessible environment, primarily due to slow movement through the UZ. With the transition to a dose-based standard, the role of the SZ has taken on increased significance, especially its role as a natural barrier as part of a defense-in-depth approach.

1. Key SZ Uncertainties

Additional SZ flow-and-transport data, both on the regional scale and the site scale, are needed. Regional hydrologic and stratigraphic data between Yucca Mountain and Amargosa Valley and other potential discharge points are nearly absent at present. This groundwater-flow domain is dominated by networks of faults and fractures and has not been characterized adequately. The total volumetric groundwater recharge to and discharge from the groundwater system under varying climatic conditions for the regional SZ model need to be understood better.

The SZ may have a greater potential as a barrier than can be demonstrated by currently available data. For example, dilution factors on a large scale cannot be measured directly and therefore must be conservatively estimated with mathematical models. The lack of appropriate data on a regional scale forces the estimation of dilution to rely on simplistic models that may underestimate potential dilution in the SZ. Recharge is likely to be greater under Fortymile Wash and other washes than it is beneath most of Yucca Mountain, and this recharge is likely to cause some dilution and dispersion. This hypothesis is difficult to verify, however, so the uncertainty in potential dilution will be difficult to reduce in the near term.

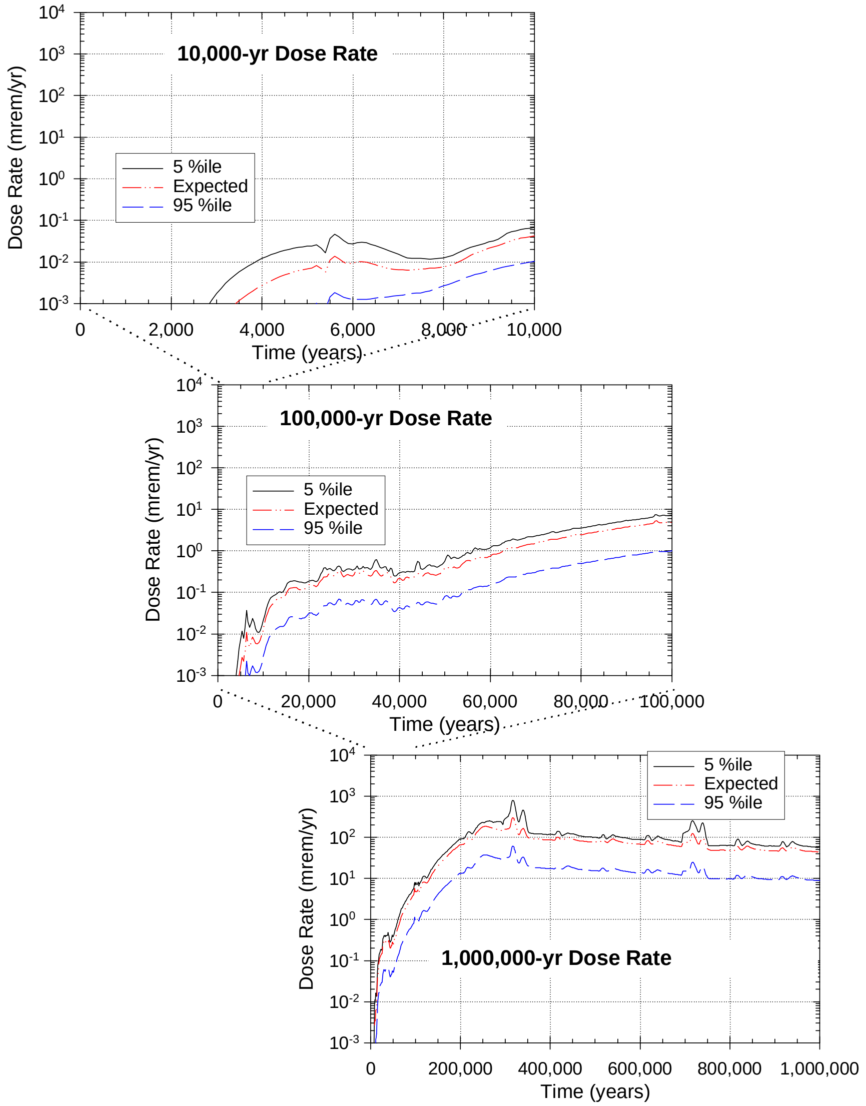
---

[12] See Chapter 4 for details.

As water travels from the volcanic rocks beneath Yucca Mountain toward Amargosa Valley and other potential discharge locations, some of the water moves into an alluvial (sand, gravel, and sediment) aquifer. Alluvium may have a high capacity for chemically retarding radionuclide movement, but there are few data that describe the retardation characteristics in fault zones and the alluvial matrix. Characterizing these features in the groundwater aquifer is a key to estimating the travel times to the accessible environment. Faults in the regional groundwater system may represent preferential flow paths or zones of high permeability. The location and hydrologic properties of such flow paths are poorly known and need characterizing.

Parts of the SZ may be a chemically reducing environment in which oxygen is absent. If so, some of the very-long-lived radionuclides that are sensitive to the oxidizing or reducing potential of the groundwater, including Np and uranium, would precipitate, permanently removing them from the groundwater and reducing predicted radiation doses at the biosphere.

Figure 1-5. Estimated Sensitivity of Dose Rate to Saturated Zone Dilution (Andrews 1998b)



2. *Addressing Key SZ Uncertainties*

The Board believes that continued single- and multiple-well testing of the type conducted at the C-well complex is necessary to bound estimates of flow-and-transport parameters on the basis of field observations. Information on the distribution of hydraulic conductivity, dispersion, radionuclide retardation, matrix diffusion, and colloid transport is needed.

The Nye County drilling project envisions 21 wells, some shallow and some deep. This drilling project, in conjunction with the proposed U.S. Geological Survey (USGS) testing program, should provide data on the three-dimensional characteristics of the regional flow system and the geochemical character of water near the tuff-alluvium interface. The deep wells in this drilling program will penetrate the regional carbonate aquifer, which has been a major uncertainty in the regional flow models. (Only one well currently provides data on the regional carbonate system in the area of interest.) The data collection in this program could be completed during the next 2 years, although analysis may require additional time.

More data are required to support modeling of the SZ, especially for the regional flow system between the repository and the accessible environment 20 to 30 km away. The flow-and-transport model should be revised as data from these new and continuing site-characterization efforts become available. Useful new regional geochemical data acquired within the next 1 or 2 years could help "fingerprint" groundwater derived from various sources and help estimate residence times. The results of this focused data-gathering and interpretive work on the SZ would add substantially to the present understanding of the potential performance characteristics of this element of the natural system, although field testing and monitoring should be an ongoing feature of work at Yucca Mountain.

III. Assessing Repository Performance

The DOE has developed total system performance assessment (TSPA) as a primary method for projecting the performance of the overall repository system.[13] The TSPA is a series of models that work together to project a variety of possible outcomes, such as how much waste will be released from a repository or the radiation doses individuals from a "critical group" will receive over 10,000 or more years. The methodology tries to capture the state of scientific knowledge and accumulated data available at the time of the assessment. Because the understanding of critical features, events, and processes and the estimates of key model parameters are incomplete or have a range of potential values under various scenarios, TSPA conclusions have uncertainties associated with them. Therefore, they often are stated in terms of probabilities. This uncertainty is unavoidable and is inherent in *any* performance assessment, whether at Yucca Mountain or elsewhere.

The DOE has developed a repository safety strategy[14] (DOE 1998) that describes the following major attributes of a Yucca Mountain repository that are considered critical to isolating radioactive wastes:

- Limited water contacting the waste packages
- Long waste package lifetime
- Slow rate of release of radionuclides from the waste form
- Concentration reduction during transport through engineered and natural barriers.

Each attribute is influenced by the interactions of the natural and engineered components of the overall system. The DOE is developing and refining testable hypotheses about the performance of the components and their interactions. To test the hypotheses, the DOE is conducting laboratory and field studies, and it is using models of the repository system and its components (TSPA) to understand better how the repository system performs. In the past, the Board has urged the development of a waste isolation strategy for guiding and focusing site investigations, and it is encouraged by the DOE's progress. Refinement of the strategy should continue throughout the course of site investigations and into the initial phase of repository construction if the site is determined to be suitable and a license application is approved.

---

[13] The Board has endorsed, with some caveats, the use of TSPA in principle. See the discussion in the Board's 1996 summary report (NWTRB 1997) and the letter from Board Chairman Jared L. Cohon to April Gil, DOE, commenting on proposed changes to 10 CFR 960 (Cohon 1997).

[14] Formerly called "waste isolation strategy" and "waste containment and isolation strategy."

In the Board's view, the technical defensibility of any decision about Yucca Mountain is improved if the *level of uncertainty* associated with projections of repository performance is reduced. Thus, in the critical next few years, it is important that the DOE carries out its analyses so that the level of uncertainty in repository performance is clearly, explicitly, and accurately portrayed and shows with reasonable assurance whether the repository safety strategy can work. To achieve this goal, the DOE will need to do the following:

- Develop a repository design that preserves the principle of defense-in-depth using multiple barriers.

- Continue developing testable core hypotheses about how the Yucca Mountain system might perform as a repository, as has been initiated in the repository safety strategy.

- Gather data for testing (and rejecting, if warranted) core hypotheses.

- Demonstrate whether the conclusions about repository safety are robust enough to withstand changes in key assumptions of conceptual models and in data acquired through ongoing investigations.

IV. Summary

The current repository design for Yucca Mountain envisions the defense-in-depth that is provided by both natural and engineered barriers. Uncertainties remain about the long-term performance of each barrier, and additional studies are needed, as discussed in this report. The Board strongly supports continuing focused studies of both the natural and the engineered barriers at Yucca Mountain to attain a defense-in-depth repository design and to increase confidence in predictions of potential health effects in the future. Although there are economic and technical limits to reducing uncertainties, the Board believes that some key uncertainties could be reduced further over the next several years through a focused research effort. One line of work is to continue investigating alternative repository and waste package designs that could reduce the level of uncertainty about the performance of the overall repository system. Another is testing some of the important hypotheses about waste package materials under well-controlled conditions.

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.

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.

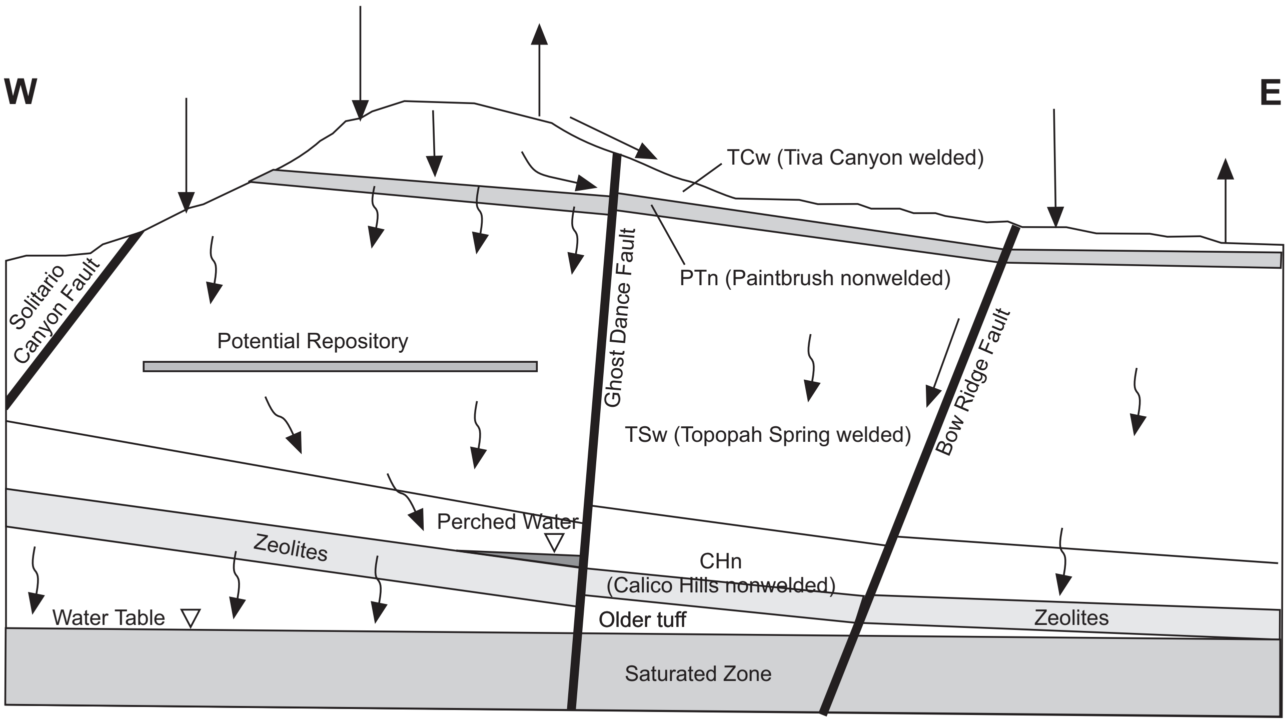
On the basis of the early studies, Montazer and Wilson (1984) of the USGS synthesized the UZ hydrology (net infiltration, percolation) and physical rock properties. They reached the following conclusions:

---

[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 $2.14\text{x}10^6$ 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 $\log_{10}(\text{Np})$ (in mol/L) ~ -5.85, instead of the value of $\log_{10}(\text{Np})$ ~ -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.

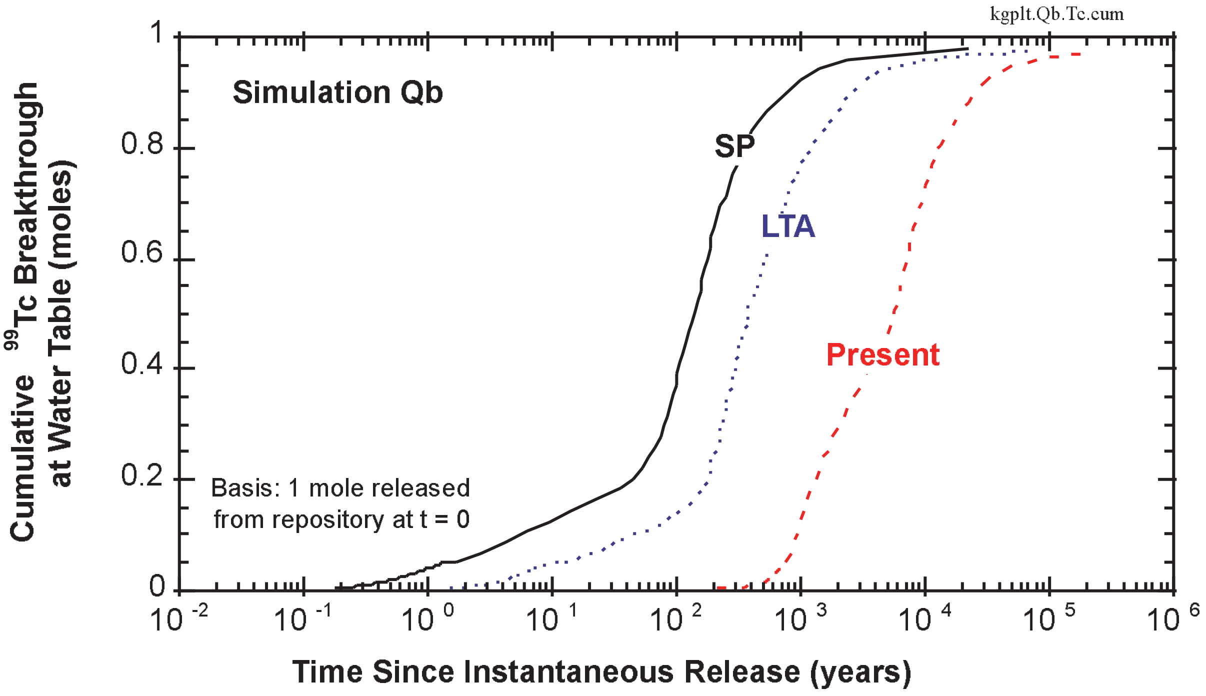
VII. Travel Times Through UZ

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.

Chapter 3

Engineered Barrier System

I. Introduction

The proposed repository consists of natural geologic barriers and engineered barriers. All of the engineered barriers together constitute the engineered barrier system (the EBS). The EBS can be divided into two interrelated components: the underground facility[1] and the waste packages.[2] The two components are discussed in this chapter.

II. Underground Facility

Before repository closure, the underground facility provides the space for emplacing waste packages, monitoring them, retrieving them if necessary, and conducting performance confirmation testing. After closure, the underground facility can contribute to performance (the ability of the repository system to contain and isolate waste) by providing a favorable, or at least a nonaggressive, near-field environment for the waste packages.

The current design of the underground facility reflects a 1995 study (CRWMS 1995a) and a DOE decision to focus on designs with high areal mass loading (i.e., 80-100 metric tons of uranium [MTU][3] per acre). The decision resulted in large part from the hypothesis that the heat from the decay of the radioactive waste could provide an above-boiling environment for waste packages for up to thousands of years and that such an environment would result in low humidity, low waste package corrosion, and therefore low waste package failure rates. A significant effect of the decision was that the entire 70,000 MTU specified by Congress as the capacity limit for the first geologic repository could be accommodated in the approximately 1,200-acre block under Yucca Mountain nominally bounded by the Ghost Dance fault on the east and the Solitario Canyon fault on the west.

The current (reference) design of the underground facility results in peak temperatures of nearly 200ºC in the tunnel (drift) walls and 250ºC on a waste package's outer surfaces. Throughout this chapter, the current design of the underground facility is referred to as the “hot” repository design to distinguish it from an alternative cooler repository design in which peak temperatures would be much lower.

---

[1] “Underground facility” means the underground part of a geologic repository where spent nuclear fuel and high-level wastes are emplaced, excluding shafts, ramps, boreholes, and their seals.

[2] ”Waste package” means the radioactive waste materials and any encapsulating and stabilizing matrix, as well as any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container (10 CFR 60). The term does not mean only the waste container. Except where otherwise stated, the discussion in this chapter is based on the current (reference) designs of the underground facility and the waste packages.

[3] One MTU is the amount of spent fuel that contained 1,000 kilograms of uranium before irradiation.

III. Current Design of Underground Facility[4]

A. Facility Configuration

The block for the underground facility would occupy about 1,200 acres under Yucca Mountain, the actual emplacement area being about 800 acres. The underground facility would consist of about 100 parallel emplacement tunnels that run roughly east to west. This orientation results in the most stable tunnels because the tunnels are at least 30 degrees from the presumed dominant joint orientations. The emplacement tunnels would be approximately 1,200 meters long and 5.5 meters in diameter and would connect at each end to a 7.62-meter-diameter tunnel that runs along the perimeter of the emplacement area. The existing north and south ESF ramps would connect the perimeter tunnel to the surface.

The waste-emplacement tunnels would have precast-concrete floor and ground-support segments. Ventilation during construction and operations would be provided by the north and south access ramps and two shafts connecting to a central north-south exhaust tunnel below the underground facility. This system would be ducted to the center of each emplacement tunnel. The ventilation system would provide separate air-flow systems for underground facility loading and construction. It would be capable of rapidly cooling a single waste-emplacement tunnel at high air-flow rates if waste packages need to be removed, for example for tunnel maintenance and repair. In this hot repository design, each emplacement tunnel would be closed immediately after it is filled, and ventilation of the closed tunnel would be reduced to a very low rate until repository closure. At repository closure, this limited ventilation would cease.

After all emplacement tunnels are filled, the underground facility would remain accessible for at least 50 years for monitoring and performance confirmation. (Recently, the DOE suggested changing the reference design so that the underground facility would remain accessible and observable for up to 300 years [Barrett 1998]). The underground facility eventually would be closed and permanently sealed.

B. Thermal Management

The areal mass loading of the underground facility would be determined by the contents of the waste packages and the spacing of the packages within the underground facility. Temperatures within the underground facility would depend largely on the areal mass loading and the degree of ventilation. As spent-fuel assemblies are received at the aboveground facilities, they would be placed in waste packages. The waste packages then would be moved to the underground facility for emplacement, generally in the same order as received at the aboveground facilities. No provision would be made for aging or mixing assemblies to lower temperatures or to obtain a more-uniform temperature distribution.

The key hypothesis of the hot repository design is that decay heat from the radioactive waste would create above-boiling temperatures that would keep liquid water away from waste packages. This low-humidity waste package environment could persist for several thousand years.[5] However, water that vaporizes in the rock would condense in cooler regions of rock farther away, and some of this condensate could flow back onto some of the packages.[6] The resulting hot and wet conditions could exacerbate waste package corrosion[7] and mobilization of radionuclides in the waste. In addition, as the underground facility eventually cools and waste package temperatures fall below boiling, hot and wet

---

4. The design information in this section is taken primarily from CRWMS 1997a and CRWMS 1997b.
5. The duration of above-boiling temperatures for the hot repository design would be determined largely by the areal mass loading of the underground facility, which is specified to be 85 MTU per acre; the age of the spent fuel at emplacement; and the percolation flux through the repository horizon. A very rough rule-of-thumb is that 1 MTU of 20-year-old commercial spent fuel generates 1 kW of decay heat. Decay heat decreases with age.
6. See Simmons and Bodvarsson 1997 for more discussion of this issue.
7. Such “refluxing” of condensate could be of particular concern if waste package materials are susceptible to pitting corrosion at temperatures marginally below boiling.

conditions can be expected. Uncertainties about how hydrologic and mechanical conditions in the surrounding rock will evolve over time make it difficult to predict the waste package environment and, thus, the ability of the waste packages to contain radioactive waste.

C. Tunnel Stability (Rockfalls and Tunnel Collapse)

The natural temperature of Yucca Mountain at the repository horizon is approximately 25°C. If the average temperature of a waste emplacement tunnel rises to 160°C (CRWMS 1997a) in the hot repository design, modeling indicates that the tunnel would expand vertically 8 to 10 mm while shrinking horizontally the same amount (Elsworth 1998). The thermal stresses causing these deformations could increase the probability of rockfalls or tunnel collapse.[8] Tunnel collapse may be thought of as the culmination of many rockfalls.

In the hot repository design, rock temperatures would peak about 50 years after waste is emplaced. The period of maximum thermal stress on the tunnel walls is thought to be during the heat-up phase and when the rock is at or near its peak temperature. If the underground facility remains accessible and observable for about 300 years, the temperatures of the rock will have decreased to around 120°C, and the rock will have passed through its period of highest stress. By then, if the rock is observed to be stable, it likely will remain stable indefinitely. If it has failed, repairs might be possible before closure of the underground facility.

Tunnel stability is important for waste package performance. For example, rocks falling from the roof of a tunnel could break through the wall of a waste package already thinned by corrosion. An analysis shows that a 350-kilogram rock falling 2.4 meters could cause the failure of a waste package that has lost 85 percent of its outer-wall thickness because of corrosion (CRWMS 1996, Barnard 1998). Even if a falling rock is not heavy enough to cause waste package failure, it could dent the waste package and the resulting depression could collect water. This situation, together with residual stresses in the struck area, could accelerate local corrosion. Rockfalls make predicting the amount and timing of water contacting a waste package more difficult because the rockfalls affect the characteristics of the rock in the tunnel roof (thereby making seepage more difficult to estimate) and affect the way that seepage is distributed before it contacts a package.

IV. Alternative Underground Facility Designs

Evaluations of alternative underground facility designs are needed, especially those that may provide at least the same level of performance with reduced uncertainty. Many aspects of underground facility design may affect performance, including tunnel diameter, waste emplacement mode (e.g., in tunnel openings, walls, or floors), degree of ventilation, and use of backfill or drip shields. For example, the negative effects and uncertainties associated with rockfalls and tunnel collapse might be reduced, or possibly eliminated, by changes in underground facility design. The following are examples of such changes:

- Using smaller tunnel diameters, which would lead to greater tunnel stability and a shorter distance for rocks to fall.
- Using backfill, which would cushion waste packages against rockfalls.
- Adopting a cooler repository design, which would reduce thermal stresses.
- Using fillers in waste packages, which would make them more resistant to penetration and denting.

One of the most important aspects of design is repository temperature. A cooler design may have the advantage of greater certainty about the hydrologic

---

[8] New methods for keyblock analysis being developed by the Yucca Mountain project may permit probabilistic assessments of tunnel stability, spatial variability of rock block sizes, and frequency of rockfalls.

and mechanical behavior of the rock surrounding tunnels and could reduce the rates of waste package corrosion and radionuclide mobilization from the waste. Lower peak temperatures also would reduce the degree of coupling between the thermal and the hydrologic, chemical, and mechanical processes—a major source of uncertainty in estimating performance. Lower temperatures could extend waste package life by preventing (or at least reducing) the period when conditions are both hot (near boiling) and wet—conditions known to exacerbate corrosion of waste package materials.

Underground facility temperatures may be reduced by aging the spent fuel before placing it in the underground facility, by using smaller waste packages and placing them farther apart to reduce the areal mass loading, by continuously ventilating the waste emplacement tunnels before underground facility closure (Danko 1997), or by a combination of the three procedures. A cooler underground facility design could use ventilation to keep the walls of emplacement tunnels below boiling, thereby reducing the degree to which water vaporizes near the wastes and moves to cooler regions where it would condense. Removal of heat by ventilation also would permanently remove some water through evaporation into the normally very dry desert air. By limiting temperatures, this design would simplify predictions of hydrologic, mechanical, and chemical conditions in nearby rocks.

There may be offsetting disadvantages of increased ventilation, more-complex fuel-aging procedures, or increased repository area. Analyses of alternative designs should illuminate the relative merits of hot and cooler designs.

V. Waste Package Design

High-level radioactive wastes include spent pressurized-water reactor fuel, spent boiling-water reactor fuel, spent research reactor fuel, and waste from reprocessing that has been solidified into glass logs. Regardless of whether such waste is measured on the basis of current or future radioactivity, more than 90 percent of the waste is spent fuel from commercial nuclear power reactors. Thus, the following discussion of the uncertainties in the long-term performance of waste packages in deep geologic repositories focuses on commercial spent fuel.

In the current design, a waste package containing spent commercial fuel has four distinct barriers. From the outside in, they are (1) a 10-cm-thick carbon-steel outer wall; (2) a 2-cm-thick nickel-alloy inner wall; (3) cladding, usually zircaloy, surrounding the spent fuel; and (4) the spent fuel itself, which consists of degraded uranium oxide ceramic pellets that contain small amounts of fission products and actinides. In general, the four waste package barriers would fail sequentially from the outside in. That is, the processes leading to failure of an inside barrier would not begin until the barrier immediately outside of it is penetrated. However, certain disruptive processes or events, such as falling rocks, could cause more than one barrier to fail simultaneously.

A. Environmental Conditions for Waste Packages

The external environmental conditions for the waste packages are the pressures, temperatures, and compositions of the gases, liquids, and solids that contact the waste packages *before such gases, liquids, and solids are chemically modified by interaction with the waste packages.* Waste packages emplaced in an underground facility at Yucca Mountain would undergo a range of external environmental conditions that would affect the rate of corrosion of the packages.

The range of external environmental conditions for emplaced waste packages is reasonably well bracketed. The gas pressure outside the waste packages would be approximately atmospheric at all times. For the current hot repository design, temperatures on the outer surfaces of the waste packages would fall within the range of 25°C to 250°C, and the relative humidity of the gas phase surrounding the waste package would range from near 0 percent to 100 percent. For a cooler underground facility design, temperatures on the outer surfaces of waste packages would fall within the range of 25°C to 150°C, and the relative humidity of the gas phase surrounding the waste package would still range from near 0 percent to 100 percent.

The composition of water in the pores of the rock in the UZ is similar to the composition of water in well

J-13 in the SZ, the main source of water for the project. However, principally because of thermal effects, water that drips on waste packages is unlikely to have the same composition as that of undisturbed pore water. Pore water in the rock near the tunnels would evaporate, leaving salts behind. Evaporated water would condense in cooler zones farther away from the tunnel walls. Conceivably, some of the water could run back into the tunnels through high-permeability zones shortly after condensing and before it has enough time to become saturated with salts. This water could be as dilute as nearly pure condensate, or it could approach J-13 water in composition. On the other hand, hot condensate could dissolve soluble salts, resulting in solutions that are more concentrated than J-13 because the solubilities of most salts increase with temperature. Solutions also could become more concentrated simply by dripping onto a hot waste package and evaporating.

Although the *range* of environmental conditions outside an emplaced waste package is reasonably well understood, *when* a given waste package would be in one part of the range or another and for *how long* are much less well understood. For example, although water would drip onto some of the waste packages some of the time, which packages would be contacted by dripping water and when they would be contacted are not known.[9] The ability to predict the timing and distribution of dripping water is important because waste packages will corrode faster if they are dripped on and, except for gaseous radionuclides, water is necessary for transporting radionuclides away from a waste package and toward the environment that is accessible by humans.

Contact between liquid water and waste packages is necessary for significant corrosion rates to occur. Predicting corrosion with reasonable confidence requires knowledge not only of the waste package materials and external environmental conditions but also of the modified environmental conditions that would evolve on (or inside) waste packages as a result of interactions among waste package materials and corrosion reactions, corrosion products, radiolysis,[10] and external environmental conditions. The modified environmental conditions on a package can vary widely over just a few millimeters, depending on where drips contact the package, the presence or absence of crevices, and the amount of corrosion that has occurred already.

A particular concern about the modified environmental conditions is the highest concentration of ferric chloride and the lowest pH to which the inner wall and waste form may be exposed. The inner wall and waste form can degrade rapidly in environments having high ferric chloride concentrations and low pH. The rate of degradation generally increases with temperature. Currently, there is considerable uncertainty about the chemical compositions of the modified environmental conditions. This uncertainty could be reduced significantly by laboratory experiments aimed at defining the range of modified environmental conditions. Calculations using existing thermodynamic models (e.g., the computer program, EQ3/6 [Wolery and Daveler 1992]) could help in guiding, interpreting, and verifying the experiments.

B. Waste Package Barriers

The four distinct barriers provided by a waste package containing commercial spent fuel are discussed below, from the outside in.

1. Carbon-Steel Outer Wall

The carbon-steel alloy for the outer wall contains more than 98 percent iron; carbon and other alloying elements make up the rest. Metallic iron is not thermodynamically stable. It eventually combines with

---

[9] As discussed in the chapter on the UZ, modeling of seepage into drifts has been attempted. Not unexpectedly, modeling results are very sensitive to local percolation flux and local rock properties, both of which are difficult to predict.

[10] As the radioactive waste decays, it generates ionizing radiation. The interaction of ionizing radiation with fluids around it is called “radiolysis.”

other substances in the environment (e.g., oxygen, water, sulfur) by means of corrosion processes to return to a condition resembling that of the ores from which it was extracted. Corrosion wastage of the outer walls of some of the waste packages is very likely within the extremely long expected time frame for the underground facility. The operating corrosion processes and the rate at which they happen would be determined by the immediate package environment. Modes of corrosion of the outer wall (and when and where they are likely to prevail) are discussed below.

a. Corrosion Modes

Iron alloys (i.e., steel) in contact with hot, dry gas may corrode through direct formation of metal oxides on the alloy surface. This corrosion mode is the most likely while package wall temperatures are well above boiling and in the absence of water dripping on the hot packages. Assuming the current hot repository design, low-relative-humidity conditions are hypothesized to persist for thousands of years for the waste packages located close to the center of an underground facility at Yucca Mountain (Stacey et al. 1997). Extensive corrosion-performance data on these service conditions are in the literature. At the temperatures and gas compositions projected for hot and dry packages, oxidation should be relatively uniform over the metal surface and very slow, resulting in negligible wastage as long as the conditions are maintained.

Iron alloys in contact with liquid water corrode by ionic dissolution of the metal into the water (corrosion products, such as rust, form afterward). Direct dripping of water on a package is not needed for this process; water may be present in the form of a very thin layer on the metal surface, even above the nominal boiling temperature if the relative humidity becomes high enough. A thin water layer is certain to form as the temperature becomes lower and humidity increases later in the life of the underground facility. Corrosion rates under those conditions can be predicted approximately from existing literature, and experiments are under way to obtain additional information,[11] but penetration of the outer wall by this type of process is expected to require times on the order of a thousand years or more.

Far more severe corrosion results if carbon steel is in direct contact with dripping water (as in a package directly below a seepage point) or is surrounded by a porous medium made moist by the surrounding environment (as in a package in a crumbling tunnel or a package surrounded by porous earlier corrosion products). Abundant information is in the literature on the corrosion rate of steel in direct contact with natural waters at various temperatures. In addition, laboratory tests measuring the corrosion rate of carbon steel (both immersed in water and in the vapor zone) at conditions approximating those expected at Yucca Mountain have been under way for nearly 2 years and are scheduled to continue for several more years (Gdowski 1995, McCright 1995, Stahl 1997). The available data indicate that the outer walls of packages exposed to these corrosion regimes are likely to be penetrated on the order of a few hundred years after water begins contacting them.

The effects of corrosion can be aggravated if the corrosion becomes strongly localized, as in the phenomenon known as *pitting corrosion*. Corrosion pits conceivably could penetrate a thick metal wall much more quickly than generalized corrosion can. In carbon steel, pitting corrosion is promoted if aggressive agents, such as chloride ions (as in concentrated pore water), are present and the pH of the surrounding water is about 10 or higher. This suggests a potentially adverse effect of using concrete extensively for underground facility construction, because concrete leachates could significantly elevate the pH of the seepage water.

---

[11] Research on thermogravimetric microbalance for determining corrosion rates of metals covered by thin water films has been under way at Lawrence Livermore National Laboratory for several years (Gdowski 1995).

b. DOE Approach

The TSPA-VA outer-wall corrosion model recognizes the modes indicated above and incorporates corrosion rates for each case that are within generally accepted levels. Long-term laboratory corrosion tests seem to be confirming the values adopted from earlier literature reviews (Stahl 1997). The model also includes a provision for the onset of pitting corrosion, using plausible aggravation factors. Continuing the work on reducing uncertainty about these projected rates is important.

The TSPA-VA model divides the package surface into individual elements (patches). Most important is the predicted number of patches that are subject to direct water contact (because the corrosion modes for the other patches are much less severe). Thus, much of the uncertainty of the present model projections derives from uncertainty in predicting the spatial and temporal distribution of water dripping on the waste packages. Extreme conditions, such as a concentrated jet of water impinging on a hot package, could even trigger an erosion-corrosion mode not considered in the discussion above that might result in penetration of the outer layer in as little as a few years (WPDEE 1998). Reducing uncertainty about seepage distribution (as discussed in the UZ chapter) is therefore crucial to a more reliable projection of outer-wall performance.

Other issues that warrant attention are performing a more detailed analysis aimed at predicting the chemistry of the water contacting the package, especially the elevated pH after interaction of underground facility water with structural concrete, and taking into account the neutralizing capacity of carbon dioxide (CO_2). Continuation of work by the DOE along these lines (Sassani et al. 1997) could help reduce uncertainty.

2. Nickel-Alloy Inner Wall

The material for the inner wall is a chromium-rich nickel-base alloy with the designation Alloy 22.[12] Nickel, chromium, and other important alloy components are not thermodynamically stable under the expected repository conditions. Instead, the alloy derives its corrosion resistance from the phenomenon of *metallic passivity*. A thin film (sometimes only a few atomic layers deep) forms on the surface of the alloy and separates the reactive metal from the surrounding environment. When this passive film is stable, the alloy becomes extremely corrosion resistant.

Interim TSPA-VA results made available to the Board show that the proposed Alloy 22 inner wall is a very important barrier for the first 10,000 years of a repository's lifetime and perhaps for many more tens of thousands of years. Therefore high confidence in performance predictions for this wall is important.

a. Present State of Knowledge

Prediction of the performance, over repository time scales, of corrosion-resistant engineering alloys that owe their resistance to the formation of passive films cannot be backed by direct experience, because these alloys have been in use for a few decades at most. Nevertheless, extensive knowledge of fundamental mechanisms for the formation and breakdown of passive films has been developed over the past half-century. Research based on that knowledge has shown that under certain severe conditions, passivity can be compromised even for highly corrosion-resistant alloys, such as Alloy 22, and that rapid corrosion ensues (Haynes 1997).

---

[12] In the last 2 years, the reference material for the inner wall has been changed to progressively more-corrosion-resistant materials: from Alloy 825 to Alloy 625 to Alloy 22. The basic composition of Alloy 825 (in weight percent) is Ni 42, Fe 28, Cr 21, Mo 3, Cu 2, and Ti 1; of Alloy 625, Ni 61, Cr 21.5, Mo 9, Nb 3.6, and Fe 2.5; and of Alloy 22, Ni 56, Cr 22, Mo 13, Co 2.5, W 3, and Fe 3.

Research also has shown that under less severe conditions (which include even highly concentrated J-13-type water near boiling), those alloys remain passivated and have extremely low corrosion rates, on the order of 0.1 micrometer per year (Stahl 1997). These less severe conditions are prevalent in present projections of the repository environment. However, partly due to lack of long-term direct experience and partly due to uncertainties about the severity of the modified environmental conditions that corrosion-resistant alloys might be exposed to in Yucca Mountain, the ability to demonstrate that these alloys would survive many thousands of years in a repository remains a matter of debate within the materials community.

Combinations of ferric and chloride ions are known to generate low-pH environments that cause passivity breakdown in corrosion-resistant alloys. These ionic combinations conceivably could result from the presence of corrosion products of the carbon-steel outer layer and chloride ions concentrated by evaporation of seepage water. Research could be conducted to determine by experiment and thermochemical calculations whether the present package design could easily generate such an environment. The outcome of that research would indicate whether the present waste package design presents the danger of failing after a relatively short time (perhaps hundreds of years) or whether the package has a chance of surviving tens, or hundreds, of thousands of years.

If research reveals that the carbon-steel corrosion-allowance metal could create such an aggressive environment, a modified waste package design could be developed with current technology to prevent the problem. For example, a modified design could use the nickel alloy on the outside and the carbon steel on the inside to retain mechanical strength. Another approach could involve using redundant layers of diverse corrosion-resistant alloys, such as Alloy 22 and a titanium alloy (another material relying on metallic passivity for its corrosion performance). Other potentially large sources of ferric ions, such as the tunnel steel sets and the steel reinforcement of the concrete tunnel walls, would need to be eliminated.

Even in the absence of external ferric ion sources, localized depassivation of high-performance alloys can occur by pitting or *crevice corrosion* if aggressive microenvironments form at the metal surface. This may occur, for example, at contacts between the metal and tunnel debris; at metal-metal openings, including surface rolling imperfections; and at places where the package rests on its pedestal. Another form of localized failure is *stress-corrosion cracking*,[13] which could affect the area of the final closure weld of the package or other points of unrelieved stresses.

The information available to date (Roy et al. 1997) suggests (but does not ensure) that Alloy 22 has little susceptibility to these forms of corrosion under the expected repository service conditions, pending resolution of the issue on chloride and ferric ions mentioned earlier. Titanium alloys can be attacked by fluoride ions (Dillon 1998), which are present in small amounts in the rock pore water and could become concentrated from evaporation. Otherwise, titanium alloys also appear to have very low susceptibility to localized corrosion under the anticipated service conditions.

b. DOE Approach

The TSPA-VA model of a corrosion-resistant alloy wall takes into account the modes of corrosion indicated above. Like the outer wall, the inner wall surface in the DOE model is divided analytically into patches with or without direct water contact. Corrosion of the patches proceeds by uniform dissolution (at rates assumed to be comparable to those observed in passive metal laboratory tests) or by localized (pitting) corrosion for a small fraction of the patches. The present choice of distribution of corrosion-rate values for uniform corrosion reflects input from the technical literature that includes some cases showing relatively high corrosion rates (McNeish 1998a). As a result of that choice, uniform

---

[13] Stress-corrosion cracking is a cracking process that requires the simultaneous action of a corrosion mechanism and sustained tensile stress.

wastage is the dominant mode of failure in the model calculations. This approach leads to typical projected times-to-failure on the order of tens to hundreds of thousands of years for the inner wall.

The number of patches in contact with water is a major source of uncertainty. Uncertainty in the values of uniform corrosion rates is being addressed by continuing long-term laboratory corrosion tests (Stahl 1997). Uncertainty in the conditions leading to the onset of localized corrosion also is being addressed in laboratory tests at Lawrence Livermore National Laboratory (LLNL), the University of Virginia, the Center for Nuclear Waste Regulatory Analyses, and the corrosion research community at large. This research is very important for reducing uncertainty in known modes of deterioration.

Galvanic protection[14] of the high-nickel alloy of the inner wall by the less noble (less corrosion-resistant) carbon steel of the outer wall once was thought to be an important contributor to performance. However, in part because of the opinions of experts on the Waste Package Degradation Expert Elicitation Panel, galvanic protection is not part of the TSPA-VA base case, although some experimental work on galvanic protection continues. If the results of this work are favorable, limited galvanic protection again could become part of the base case.

c. Issues

Recent performance assessments and the draft license application plan recently prepared by the DOE clearly indicate that the EBS is a very important link in determining the performance of the overall repository system for the first 10,000 years and longer of the repository's life. The waste package is the most critical component of the EBS.

Current and alternative waste package designs take into consideration expected corrosion mechanisms and service factors leading to the conditions where those mechanisms are present. Design teams and experts have covered many scenarios (Whipple et al. 1998, WPDEE 1998). Issues are still open involving use of available information or information from ongoing experiments. They include determining the possibility of mechanical deterioration of the inner wall by "denting" (from accumulation of corrosion products between the outer wall and the inner wall), determining in short experiments the minimum temperature for development of crevice corrosion, assessing the susceptibility of titanium alloys to hydrogen embrittlement under repository service conditions, determining the corrosion effect of sulfur-bearing aqueous species, and establishing the potential advantages of heat treating the waste package after the closure weld is completed. These issues have a good chance of being resolved in the short term.

Fundamental investigations to date have not revealed a mechanism whereby fast corrosion rates could develop in the materials considered (Alloy 22, titanium alloys), even if a moderately aggressive environment were to be maintained at the immediate metal surface. However, those materials are relatively new and have been investigated for only a limited time (decades) under any conditions and for only a few years under conditions that directly apply to the expected waste package environment in Yucca Mountain. Unlike the case of some iron or copper alloys that have been used for thousands of years, there is little or no comparable experience with alloys of metals that rely on passivity for corrosion protection.

This is a critical issue because the history of corrosion has sobering examples of unexpected modes of failure of materials that had otherwise good service prognoses (Dillon 1998). Central to this issue is understanding how stable metal passivity can be over the extremely long repository time scale. Answering that question may require reexamining the present theoretical base on metal passivity (Macdonald 1992). Other subtle effects on corrosion performance that may fail to show up in short-term experiments but that could prove critical in millennial time frames may include slow phase transitions, effects

---

[14] Galvanic protection is protecting a metal from corrosion in the presence of an electrolyte (such as water containing dissolved salts) by providing physical contact with a more electropositive metal, which will corrode first.

of ionizing radiation on corrosion properties, and low-dose radiolytic phenomena.

Waste package performance depends not only on the base of knowledge of materials performance, but also on how that base of knowledge is applied. In particular, quality control in manufacturing is critical. In the present TSPA-VA formulation, juvenile failures resulting almost entirely from manufacturing or handling errors are the single dominant source of exposure to the public during the early repository service life. This underscores the importance of advancing a credible and implementable plan for quality control in manufacturing.

Because of the importance of waste package performance, a major limit on any efforts to project the corrosion behavior of the packages must be understood. That limit is the assumption that no unknown mechanisms will affect the integrity of the packages over the long time of interest. This assumption, usually implicit, is crucial to the value of any service-life projection.

3. Zircaloy Cladding

Currently, the DOE plans to take performance credit for zircaloy cladding in the base case of TSPA-VA. Data on general corrosion of zircaloy cladding are extensive (Franklin 1997, Hillner et al. 1998). Most of the data are on conditions within nuclear reactors that arguably are significantly different from the modified environmental conditions that Yucca Mountain would impose on zircaloy cladding. If zircaloy cladding is exposed to environments that are strongly acidic and severely oxidizing, pitting corrosion is possible. Although such an environment *outside* the waste package is unlikely, the possibility of its occurrence *inside* some emplaced waste packages has not been ruled out.

What needs to be determined is whether the combined interactions of corrosion products from the inner and outer walls, radiolysis, water, and elevated temperatures could produce a corrosive environment inside waste packages. Both theoretical work (e.g., using computer programs that model thermodynamic equilibrium) and experimental (laboratory) work are needed to predict the ranges of local environmental conditions that could exist inside a waste package and the probabilities of their occurrence. The importance of the work to the performance of the zircaloy cladding is an additional reason that the experimentation and modeling discussed earlier in this paper should be done to determine the environments of materials inside the waste package.

Zircaloy cladding may be an exception to the general rule that barriers fail sequentially from the outside. Corrosion caused by pellet-cladding interaction (PCI)—stress-corrosion cracking from the inside of the cladding caused by the interaction of spent-fuel pellets and the cladding—has been studied, but is not fully understood. In addition, about 1 percent of commercial spent fuel is clad in stainless steel, and about 1 of every 1,000 zircaloy-clad spent-fuel rods may arrive at the underground facility showing cladding penetration (Siegmann 1997). According to the DOE, intact fuel rods would not fail (defined as the first pinhole penetration) by general corrosion until many thousands of years after water first contacts them (McNeish 1998b). However, rockfalls or other mechanical forces may cause rod failure as soon as the inner and outer walls of the waste package corrode to the point where they no longer protect the rods.

Except for PCI, sufficient data exist to predict the *general* corrosion behavior of cladding in the underground facility. Predicting the contribution of zircaloy cladding to long-term performance may be difficult, however, because (1) a small fraction of the cladding already would have failed during nuclear power plant operation; (2) few data exist for estimating the damage (if any) to cladding during storage (particularly dry storage), handling, and transportation and the effects of such damage on performance; (3) little study has been done of the potential for cladding damage in an intact container (e.g., by radiolysis of water or air inadvertently trapped in the waste package during loading); (4) the potential for hydride embrittlement of irradiated zircaloy cladding has not been addressed fully; (5) limited study has been done of the degradation of cladding after a waste package is breached; and (6) essentially no data exist on the extent of *localized* corrosion of zircaloy under Yucca Mountain conditions.

4. *Spent-Fuel Pellets*

When water reaches the spent-fuel pellets, the fission products and actinides in the pellets begin to dissolve. The amount of each fission product and actinide that can dissolve in a unit quantity of water depends on the solubility of each material, which is influenced by the specific chemical composition of the water. Thus, it is important to know the conditions that would evolve on and inside waste packages as a result of interactions between waste package materials and corrosion reactions, corrosion products, radiolysis, and external environmental conditions.

The solubilities of many fission products and actinide species are known reasonably well in a variety of environments. Despite several studies,[15] however, a high degree of uncertainty remains about the solubilities of various forms of neptunium, a constituent of spent fuel that appears to be the most important contributor to doses far into the future. The solubility of neptunium is discussed in the UZ chapter of this report.

C. Waste Package Enhancements

Currently, the DOE, through its M&O contractor, is studying enhancements to the current design of the waste package. Two often-mentioned enhancements under study are *drip shields* and *ceramic coatings.*

1. *Drip Shields*

A drip shield is anything placed on or over a waste package to protect the package from dripping water. An example of a drip shield is a thin (e.g., 5 mm) semicircular sheet of metal (e.g., a titanium alloy) completely covering, conforming to, and resting on the waste package. Another example is a thicker self-supporting semicircular metallic sheet that sits slightly above a waste package rather than resting on it.

Design issues associated with drip shields include how to protect a drip shield from rockfalls and how to ensure that the drip shield remains in place. Placing backfill over a drip shield to cushion it from rockfalls and prevent it from moving is one of the ideas advanced by the M&O. If backfill that provides a high degree of capillary action (e.g., a Richard's barrier) were used, it could replace the drip shield completely, at least for low drip rates.

Issues concerning drip-shield materials are largely the same as issues concerning the waste package inner and outer walls and the zircaloy cladding—that is, the validity of models for predicting drip shield corrosion rates and the adequacy of the data on which the models are based. If the drip shield material is the same as the inner-barrier material (Alloy 22), then models and data used to predict inner-barrier lifetime would be equally useful for predicting drip shield lifetime. If the drip shield uses a different material, the adequacy of models and data for predicting its lifetime would need to be addressed on a case-by-case basis.

2. *Ceramic Coatings*

Conceivably, a thin coating of ceramic material could protect the waste package. This subject requires much research, however, to determine whether long-lasting ceramic coatings can be manufactured without flaws (e.g., cracks) and whether ceramic coatings are sufficiently resistant to handling and thermal stresses.

D. Alternative Waste Package Designs

In contrast to waste package enhancements, which are features added to the existing design to supplement its performance, alternative waste package designs are major revisions of the current design or its replacement by new concepts. In the Board's most recent summary reports to Congress and the Secretary of Energy, the Board urged the DOE to examine alternative designs (NWTRB 1997 and 1998a). Examples of alternative waste package designs include (1) a waste package with inner and outer walls of two corrosion-resistant materials (e.g., a titanium alloy and Alloy 22), rather than the current design that

---

[15] The studies have been summarized by Sassani and Siegmann (1998).

uses an outer wall of a corrosion-allowance material (carbon steel) and an inner wall of a corrosion-resistant material (Alloy 22) and (2) reversal of the order of the inner and outer barriers (an outer barrier of Alloy 22 and an inner barrier of carbon steel). These and other alternative waste package designs were discussed at the recent workshop conducted by the Board's Panel on the Repository (NWTRB 1998b).

Although analysis of alternative waste package designs to date has been very limited, alternatives using Alloy 22 or titanium alloys as the *outer* wall appear to obviate one significant uncertainty of the current design: whether the modified environmental conditions (i.e., potentially high ferric chloride concentrations and low pH) that *might* result from interaction of the current design's steel outer wall and the external environment would be corrosive to the nickel-alloy inner wall.

E. Other Waste Package Issues

1. Juvenile Failures

Juvenile failures of waste packages are premature failures. That is, they are failures that occur before a waste package would be expected to fail in an underground facility because of corrosion or other degradation processes. Juvenile failures do not include failures that are due to disruptive events (e.g., volcanism, human intrusion). The following examples are some potential causes of juvenile failures:

- A waste package is fabricated from materials containing a significant flaw (e.g., a large void in the metal plate used to fabricate the package), and the flaw is not detected during the inspections before emplacement or during the performance confirmation period.

- The final closure weld of a waste package is done incorrectly, creating a flaw, and the flaw is not detected in subsequent inspections.

- A waste package is mishandled (e.g., dropped) during emplacement in a way that seriously damages it, and the drop is not reported.

The DOE recognizes the potential for juvenile failures and has studied the issue. The TSPA-VA base case includes juvenile failures (McNeish 1998a).

2. Manufacturing, Waste Package Closure (Welding), and Nondestructive Examination

Manufacturing a waste package, making final closure welds on it, and performing nondestructive examination of the package and its welds are well within the general state of the art. Nevertheless, significant specific development work remains, and prototype waste packages need to be constructed to perfect manufacturing, welding, and examination procedures and equipment. To date, the DOE has advocated a construction method involving shrinkfitting the inner and outer walls of the waste package. Shrinkfitting[16] is easy to do, but it introduces many uncertainties—particularly about the effects of residual stresses from the shrinkfitting operation and about procedures for final closure welding. Loose-fit construction could eliminate the uncertainties involved in shrinkfitting without introducing significant new uncertainties.

3. Long-Term Research and Monitoring

The present state of knowledge suggests, but does not prove, the capability of the waste package to contain spent fuel for hundreds of thousands of years. Continuing materials research and monitoring is vital for at least several decades into the period of underground facility operations, and probably until underground facility closure. The research would include monitoring of emplaced waste packages, placement of corrosion-test samples in and around emplaced packages, laboratory experiments, and analyses. There are at least three important reasons for this research:

---

[16] Shrinkfitting is joining (or mating) layers of metal by using heat to expand an outer shell, inserting an inner shell, and allowing the outer shell to cool around the inner shell.

- Confirmation of long-term predictions (e.g., corrosion rates, phase stability) that were based on short-term data.

- Reduction of the possibility that unknown mechanisms or defects exist that could compromise performance (in particular, the nature and long-term stability of protective films).

- Investigation of innovative packaging techniques or materials offering cost saving or improved performance.

4. *Criticality*

The probability and consequences of postclosure criticality[17] have been analyzed extensively by the DOE, particularly in the last 2 years. For commercial spent fuel, the analyses indicate that criticality incidents are unlikely and that the occurrence of criticality would have minor consequences. Some wastes, particularly highly enriched spent fuel (e.g., from some research reactors), can be more difficult than commercial spent fuel to analyze for criticality.

VI. Conclusions

The engineered barrier system, that is, the underground facility and waste packages working together, performs a vital role in the operational and postclosure performance of the geologic repository. The Board’s conclusions about EBS issues are summarized below.

- Evaluations of alternative concepts for underground facility design are needed, especially of concepts that may provide the same level of performance but with less uncertainty than provided by the current underground facility design. For example, a ventilated repository design with lower peak temperatures could reduce current uncertainties about the heat-induced hydrologic, mechanical, and chemical changes in the rock surrounding tunnels and could reduce the rates of waste package corrosion and radionuclide mobilization from the waste.

- Predicting the performance of a waste package design is a matter of predicting the external (tunnel) environment of the waste package, how the waste package and its environment would interact to modify the environment, and how the materials used in the waste package would degrade (corrode) in response to the environment. High confidence in performance predictions for the nickel-alloy inner wall of the current design is needed because of its importance to waste package longevity. Research could determine if the present package design could easily generate, beneath the remains of the carbon-steel outer wall, an environment aggressive enough to deteriorate the corrosion-resistant alloy quickly. Research also is needed to confirm long-term predictions (e.g., corrosion rates, phase stability over tens of thousands of years). These predictions are based on knowledge gained during only the past several decades for materials that rely on passive films for corrosion protection and on data gained during only the past year or so for Alloy 22 under Yucca Mountain conditions.

- Several alternative waste package concepts include outer walls of high-performance materials, such as titanium alloys or Alloy 22. These alternatives offer the promise of lasting tens of thousands of years or longer, given the range of environmental conditions and the spatial and temporal distribution of dripping that may be found within the underground facility. Adoption of one of these concepts could substantially reduce part of the uncertainty associated with the current waste package design. Research still would be needed, however, to confirm the viability of the alternatives.

---

[17] “Criticality” means the development of a self-sustaining nuclear fission reaction.

Chapter 4

Saturated Zone

I. Overview

The saturated zone contributes as a natural barrier in two ways: (1) It delays the transport of radionuclides to the accessible environment (increases the travel time) and (2) It reduces the concentration of radionuclides that entered from the UZ before they reach the accessible environment (causes dilution).[1] Characterization of the SZ has been influenced to a certain extent by the regulations that existed in the past. Under the previous release-based standard, dilution in the SZ did not play a significant role. Only the delay aspect of the SZ was important because of the requirement for a minimum groundwater travel time at the site (10 CFR 60). Now that a change is anticipated from a release-based to a dose- or risk-based standard, the SZ is a more important natural barrier because of its potential to decrease radionuclide concentration (DOE 1998). Dilution is particularly important for reducing the peak dose from very-long-lived radionuclides (e.g., ^{237}Np), where delay does not result in significant radioactive decay.

The flux of water percolating (flowing) down through the UZ at Yucca Mountain is small (on the order of 7 mm / yr in the current climate) in comparison to the groundwater flux laterally in the SZ below Yucca Mountain. Although there is a large spatial variability of the lateral flux in the SZ, the average flux is thought to be on the order of 1 meter / yr, more than 100 times the estimated downward flux in the UZ. The UZ flow is expected to “mix” to a certain depth and thus be diluted by the larger volume of water flowing in the SZ (Sevoughian et al. 1995). However, the amount of dilution through mixing is highly uncertain and difficult to verify. There are no data at Yucca Mountain to determine the amount of mixing that could occur at the SZ-UZ interface. There also are no data to substantiate how much the radionuclide-contaminated plume will spread as water flows from the repository to the accessible environment.

Radionuclide dilution and travel times are directly related to repository performance. They address the “How much will arrive?” and “How long will it take?” aspects of the SZ. Other aspects also can be important, even though they might not directly influence the computed dose. One is “Where will the radionuclides arrive?”—i.e., the present and paleodischarge points. Another can be the total water budget in the flow system and its relation to withdrawal in Amargosa Valley. Thus, characterization of the SZ should not be limited to information deemed necessary to performance assessment.

II. Regional SZ Groundwater Flow

A. Stratigraphy

The SZ at Yucca Mountain lies between 500 and 700 meters below the surface. The dominant recharge of water to the SZ occurs north of Yucca Mountain at higher elevations, where precipitation is greater and

---

[1] The dilution factor for the SZ is defined as the ratio of the average radionuclide concentration in groundwater entering the SZ from the UZ to the average radionuclide concentration being withdrawn from the SZ for human use.

temperatures are lower. The dominant flow direction in the SZ from the Yucca Mountain site is southeast toward and below Fortymile Wash, then south to Amargosa Valley, as shown in Figure 4-1.

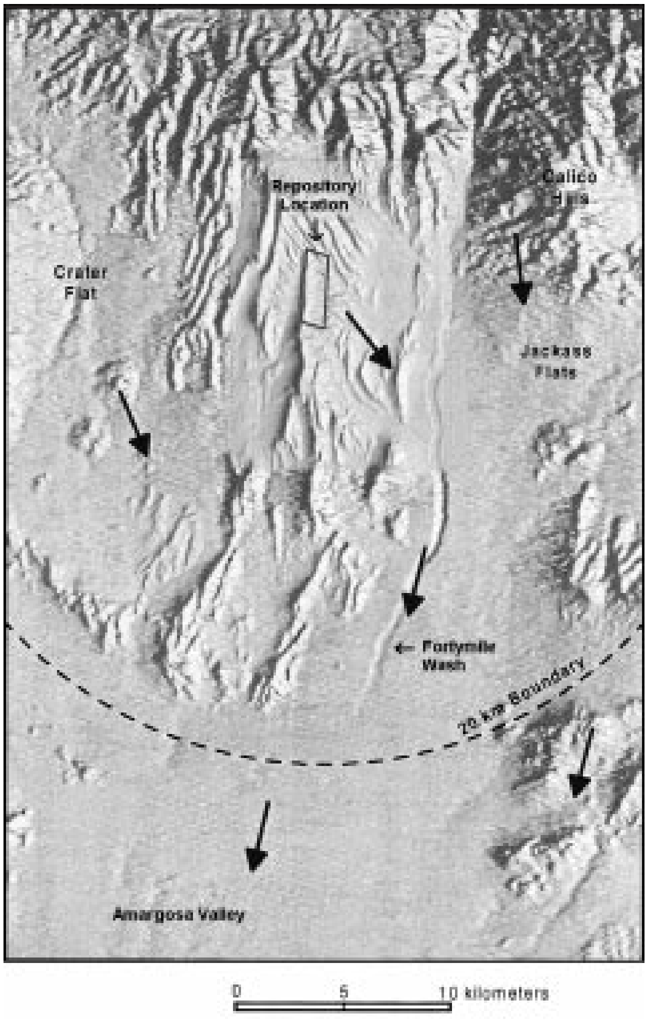
The primary hydrogeologic units that carry and influence the flow are the volcanic aquifer (consisting of the Upper Tram, Bullfrog, and Prow Pass formations), the volcanic aquitards (confining units) of the Calico Hills formation, the underlying and more permeable Paleozoic carbonate aquifer, and, to the south, the valley-fill alluvium. An idealized geohydrologic cross section from Yucca Mountain to Amargosa Valley is shown in Figure 4-2.

Based on data showing that the water pressure in the carbonate is higher than in the overlying volcanic aquifer and on numerical modeling, the general belief (SZEE 1997, D'Agnese et al. 1996) is that the downgradient flow paths emanating from Yucca Mountain primarily stay within the volcanic aquifer and, farther south, within the valley-fill alluvium. These flow paths probably do not penetrate the carbonate aquifer close to Yucca Mountain.[2] However, insufficient hydrologic and stratigraphic data downgradient between Yucca Mountain and Amargosa Valley make the models and their interpretations uncertain.

B. Hydraulic Conductivity

An important factor in the TSPA is the magnitude of groundwater flux at the top of the SZ beneath Yucca Mountain (Sevougian et al. 1995). At the water table beneath the site, the dominant aquifer carrying the flow is a volcanic aquifer consisting of the Prow Pass, upper and lower Bullfrog, and Tram units,[3] the lower Bullfrog being the most transmissive. To estimate the groundwater flux in a unit, one must know the spatial distribution of hydraulic conductivity of that unit and the hydraulic gradient.

Figure 4-1. Plan View of Flow System (after D'Agnese et al. 1996)



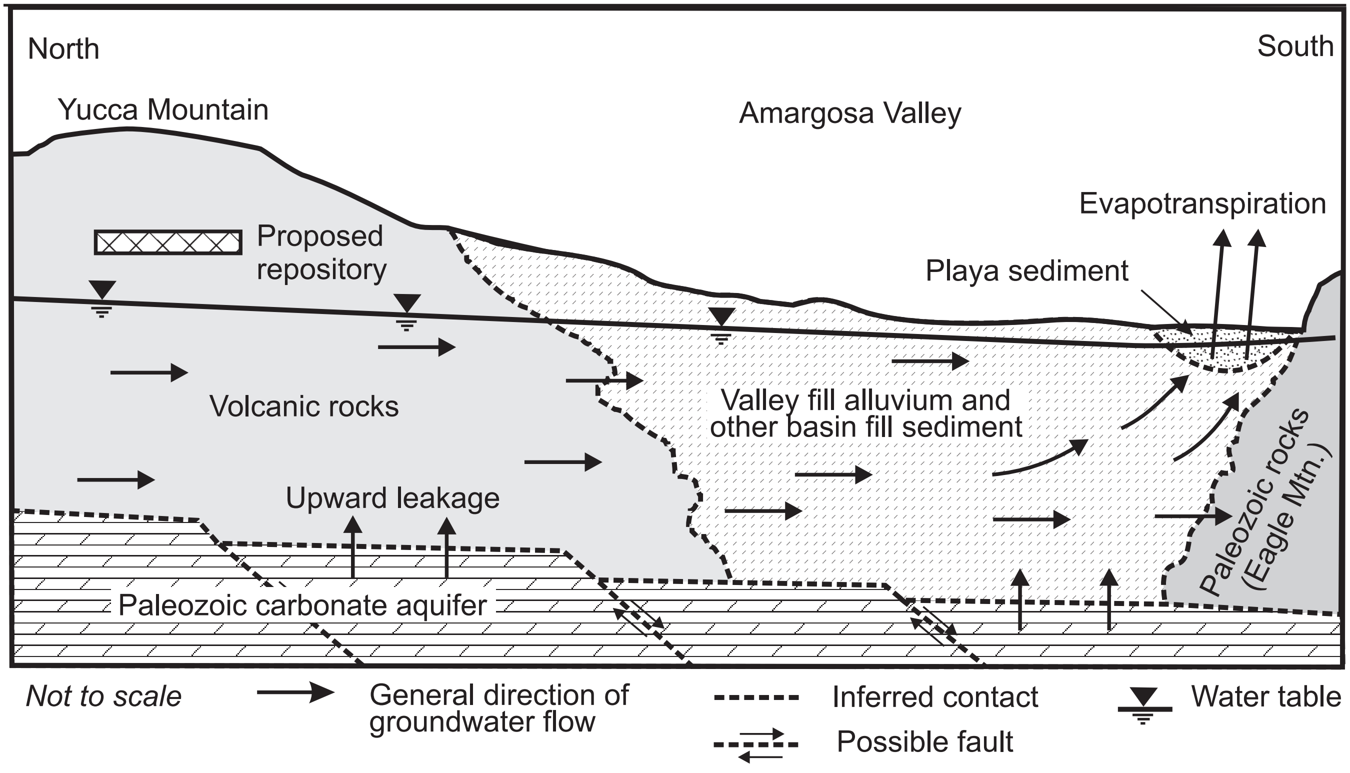
The primary uncertainty is in the estimation of hydraulic conductivity because relatively few data at the appropriate scale are available. The most reliable data come from the recent testing at the C-well complex (Geldon et al. 1997). The C-well data are from multiple-well pumping tests, which are generally more reliable than single-well tests. The C-well tests were designed to test the Bullfrog unit; single-well test results are available for the other units. Continuing the C-well pumping tests longer so that hydrologic

---

[2] This conclusion is based on a single measurement of the pressure head in the carbonate aquifer.

[3] These units are part of the Crater Flat undifferentiated rock group shown in Figure 1-1.

Figure 4-2. North-South Cross Section of SZ (after Czarnecki 1989)



information could have been obtained on a larger scale would have been fruitful. Upon evaluating the set of available data, the Saturated Zone Expert Elicitation (SZEE) Panel assessed an average uncertainty of two orders of magnitude for hydraulic conductivity for the upper and lower volcanic aquifers (SZEE 1997). This uncertainty carries over to the uncertainty about the flux beneath the site.

Additional tests at the C-well complex or other field studies, perhaps on the main block, would reduce this uncertainty and greatly increase the confidence of the SZ site-scale modeling. These tests could be carried out in several distinct units of the volcanic aquifer and over sufficient time-space intervals. The data could be obtained within the next several years. Having these test plans reviewed by an outside group, such as the panel that was convened for the expert elicitation project (SZEE 1997), before the plans are implemented also would be useful. Such a review would add confidence that the testing will obtain the required information on the SZ.

C. Channeled Flow

Because the region has been tectonically active, the regional hydrogeologic environment is structurally complex and characterized by locally high permeabilities that are due to faults and fractures. Most of the flow appears to be channeled in preferential flow paths, which, on the basis of flowmeter data obtained from boreholes, appear to represent only 5 to 20 percent of the thickness of the hydrostratigraphic units.

The role of the major faults and fracture systems is judged very important, although to what extent these features need to be—or accurately can be—included explicitly in the hydrologic model is not clear (SZEE 1997). Because the location and hydrologic properties of the faults are poorly known, model predictions of transport will have a large uncertainty (i.e., the pathway taken by the radioactive plume will be difficult to predict). In the past, little effort has been made to characterize the hydraulic conductivities of faults and fault zones, despite their potential significance. The DOE plans to evaluate the hydraulic significance of the Solitario Canyon fault zone as well as other possible faults.

D. Water Budget

The main recharge to the SZ comes from farther north, as well as from Fortymile Wash, but there is uncertainty about the total volumetric recharge of groundwater to the regional groundwater system. The discharge areas of the regional flow system are known, but the volumetric discharge from the regional system is not well constrained. Recently, efforts have been made to estimate evapotranspiration in the Ash Meadows and Franklin Lake Playa areas more accurately, but the magnitude of discharge is still considered approximate within Oasis Valley, Death Valley, and Amargosa Valley (Paces et al. 1996). The total recharge and discharge of water into and out of the groundwater system is an important constraint on the regional and site-scale groundwater models. Currently, water usage in Amargosa Valley is a significant fraction (~20 percent) of the estimated total water budget and can be expected to increase in the future.

E. Nye County Early Warning Drilling Program

DOE funding has been allocated for Nye County's proposed system of wells approximately 5 km downgradient of Yucca Mountain. Twenty-one wells are contemplated: 15 wells in the 500- to 1,000-ft depth range and 6 deeper wells for penetrating the carbonate aquifer and determining the hydraulic heads there. The 21 wells will be distributed roughly perpendicular to the direction of anticipated groundwater movement from Yucca Mountain, approximately at the interface of the volcanic rocks and the alluvium (see Figure 4-2). Considerable data will be obtained from these wells over the next 3 years (and beyond) that will form a baseline of the present conditions in the SZ at this location and that will fill in key data gaps for the SZ regional flow system. The gathered data, including geology and stratigraphy, pressure head, water chemistry, and isotopic data, should substantially increase confidence in the regional-scale modeling effort.

III. Conceptual Model of Radionuclide Transport in SZ

A. Groundwater Travel Times

Highly transmissive zones controlled by faults are believed to exist in the SZ (Geldon et al. 1997), as evidenced by the regional distribution of paleo-spring deposits and modern springs that are associated with known faults (Paces et al. 1996). In such highly heterogeneous systems, groundwater travel times are highly variable and the first arrival times can be quite short (on the order of a few hundred years), but there are no direct data that support this estimate. The travel-time distribution through the volcanic aquifer to the accessible environment 20 to 30 km away is not known. In highly heterogeneous systems, the distribution of travel times can best be estimated by conducting a tracer test on the length scale of interest, or at least on a scale that is relevant to the model requirements.

Base-case TSPA-VA models predict travel times through the SZ that are comparatively short—e.g., for most calculations, the breakthrough curves for nonretarded technetium-99 show that 50 percent of the peak concentration at the accessible environment is reached between 500 and 2,000 years. Thus, the SZ travel times, as modeled in TSPA-VA, are significantly shorter than the likely regulatory period of 10,000 years. Current estimates indicate that the SZ by itself will not sufficiently delay the radionuclides in the event of juvenile (premature) failures of the waste packages.

B. Dilution Through Mixing and Diffusion-Dispersion

Two important natural processes in the SZ that reduce the radionuclide concentrations are (1) mixing of the UZ flux with SZ water at the UZ-SZ boundary and (2) spreading of the radionuclide plume by molecular diffusion and hydrodynamic dispersion during flow through the SZ to wells or natural discharge locations. The amount of dilution that will occur in the SZ has been one of the key uncertainties in assessing the performance of the natural barriers. The primary reason is that dilution factors cannot be measured directly and require model predictions.

TSPA-95 assumptions and models, including some mixing of groundwater during withdrawal from a well, yielded dilution factors for the SZ of about 1,000 to 10,000.

In post-TSPA-95 computations, the DOE-M&O's SZ transport model assumed that the UZ flux mixes instantaneously with the SZ water to a depth of 10 meters (the depth of a computational cell). The plume then was reduced further in concentration because of a large (assumed) transverse dispersion (spreading) as it moved through the SZ. Even though the maximum computed concentration in the plume was used for dose computations, these assumptions led to dilution factors in the range of 15 to 200 (Arnold 1998). Dilution due to water withdrawal was not included in these computations.

The dilution factor was discussed thoroughly by the expert panel during the SZEE meeting in 1997; their findings are summarized in their report (SZEE 1997; individual expert commentaries). The consensus of the panel members was that mixing and hydrodynamic dispersion probably are not as effective in spreading the plume as the models had predicted. The numerous faults and the complex stratigraphy make predicting the flow path of the plume and the amount of mixing that might occur along this path very difficult. The experts' interpretation was that the concentration within the plume will not significantly decrease, but rather that the uncertainty about where the plume will emerge is high (i.e., the probability of it being at a specified location is low). The average estimate for the dilution factor from the expert panel was ~10, considerably lower than the 15 to 200 range in the initial TSPA-VA computations.

Because of the lack of data and the unsubstantiated assumptions, radionuclide transport in the SZ is being modeled for TSPA-VA by a one-dimensional stream-tube model. The dilution factors for each stream tube will be sampled randomly from the elicited expert probability distribution functions (range of 1 to 100, expected value of 10) for the dilution factor (Andrews 1998a).

There is some potential that dilution could occur because of infiltration in Fortymile Wash. As the recharged water percolates downward and reaches the water table, it could mix with the underlying plume that would leave Yucca Mountain, lowering its concentration. Conceptually, this process appears possible, but it would be difficult to verify quantitatively.

A shift to a dose-based regulatory standard, as has been recommended by the National Research Council (NAS / NRC 1995), would make estimating how much dilution could occur during SZ transport more important. The current lack of data over the 20- to 30-km distance to the accessible environment (as anticipated in the forthcoming regulatory criteria for a Yucca Mountain repository) makes estimating dilution with any confidence difficult. Thus, the TSPA-VA SZ model relies primarily on the expert elicitation estimates of the dilution factor (average dilution factor of 10). The present estimates of dilution in the SZ (base-case TSPA-VA) could be too pessimistic, just as the earlier TSPA model predictions were too optimistic.

C. Retardation

The SZ is highly variable in its hydraulic properties, and highly transmissive (fractured) regions are known to exist (Geldon et al. 1997). Estimating how much retardation will occur in these fractures is difficult. A considerable fraction of the flow might bypass the sorptive minerals in the volcanic material of the SZ by staying in the highly transmissive (permeable) regions. In that case, if retardation is to be an effective process, matrix-diffusion (the transfer of radionuclides from fractures to the matrix by diffusion) will have to occur.

Retardation may not be as effective in the field as it is when measured in the laboratory in batch experiments, especially where fracture- and fault-controlled flow dominates. Tracer tests at the C-well complex were designed specifically to quantify the processes of retardation and matrix-diffusion in the Bullfrog unit. The experiments provided initial information about the transport of simulated colloids and retarded and nonretarded dissolved species through the fractured Bullfrog unit.

Retardation in the alluvium farther away from Yucca Mountain could be more significant than retardation in fractured tuff. Currently, there are no data that corroborate this hypothesis, although experiments using the proposed Nye County wells could be used to acquire such data.

D. Colloids

The role of colloids in radionuclide transport is discussed in the UZ chapter of this report. Additional data that can be extrapolated to transport of colloids in the SZ are expected from the new experiments planned for the UZ at Busted Butte.

E. SZ Geochemistry

The solubilities of some of the elements in HLW and SNF, including Np and uranium, are sensitive to the oxidizing or reducing potential of groundwater. In the UZ, where water will be oxidizing, these elements may be relatively soluble. However, if the dissolved species are transported into areas of the SZ where conditions are reducing, they will become much less soluble and will precipitate in the same way uranium naturally precipitates to form uranium ore deposits. The precipitated species would be permanently removed from groundwater, with a consequent reduction in predicted radiation doses at the biosphere.

It seems likely that at least some parts of the SZ between Yucca Mountain and the biosphere will have reducing groundwater chemistry. Evidence of reducing conditions would include the presence in groundwater of dissolved methane, H_2S, or Fe^{++}; the absence of dissolved oxygen; and measured Eh (redox potential) values. Geochemical studies of groundwater in the Nye County wells (and possibly at other sites closer to Yucca Mountain) are needed to determine the extent to which reducing conditions may exist in SZ groundwater.

F. Mixing at the Wellhead

Considerable dilution can occur during groundwater withdrawal from an extraction well or wells. The capture zone of a production well could be greater than the dimensions of a radioactive groundwater plume, thereby causing the plume to mix with a considerable amount of fresh water (e.g., the production could be from several stratigraphic intervals, but the contaminated water could be localized in a single interval). Another scenario could be that pumped water from several wells is mixed and distributed to a local population. Thus, even in the case where the plume is basically intact (not dispersed), the process of mixing at the wellhead could produce significant dilution—e.g., up to several orders of magnitude, depending on the specifics of withdrawal. It is plausible that dilution at the wellhead can be quantitatively greater than dilution that occurs through naturally occurring processes in the SZ. Present TSPA-VA estimates assume that the average dilution factor through natural processes is approximately 10, but the distribution of values is skewed to lower values.

Expanded groundwater withdrawal within the Amargosa Valley is almost certain. The carrying capacity of this aquifer will vary for various assumed rates of recharge, i.e., present climate, 1,000-year climate, and superpluvial climate. The USGS regional model is being extended to evaluate the transient effects of climate change and pumping in the Amargosa Valley so that the dose to a “critical group” under varying climatic conditions can be predicted.

TSPA-VA will not use a well-withdrawal scenario for additional dilution at the wellhead but will use the computed maximum concentration in the plume at a distance of 20 to 30 kilometers. Thus, the dilution due to SZ transport will be very small in TSPA-VA.

IV. Influence of Climate Change

The climate has changed in the past and will change during the next 10,000 years, most likely to wetter conditions. Increased precipitation will lead to greater infiltration and an increased percolation flux. The regional recharge will increase, as will the groundwater flow volume, and the water table will rise. Past increases in the water table, up to 100 meters above the present, have been documented through geochemical and paleo-discharge evidence. Thus, the effects of climate change on precipitation, infiltration, and percolation are conceptually understood, although the precise magnitude and timing of the changes are uncertain.

The effects of climate change on repository performance can be modeled in a TSPA as an assumed increase in the percolation flux, a rise in the water table, and an increase in the water flux in the SZ. The DOE's base-case analysis for TSPA-VA considers three climate states, as described in the UZ chapter of this report. As noted above, because of the lack of data, the SZ radionuclide transport is being modeled by one-dimensional stream-tube models. Climate change will be represented as an increased flux in the SZ (i.e., in each stream tube), a rise in the water table, and reactivation of paleo-discharge points.

V. Conclusions

The Board believes that the SZ is an essential natural component of a defense-in-depth repository design for Yucca Mountain. The following are the Board's conclusions about the SZ.

- Groundwater appears to move through the SZ from Yucca Mountain to the accessible environment 20 to 30 km away in less than the likely regulatory period of 10,000 years. Although retardation in fractured rocks may be ineffective because highly transmissive regions within the SZ may allow dissolved radionuclides to bypass sorptive minerals, retardation in the alluvium near Amargosa Valley may be greater. If so, the SZ could significantly delay transport of radionuclides between the repository and the accessible environment.

- Parts of the SZ may be a chemically reducing environment where some of the very-long-lived radionuclides, including Np and uranium, would precipitate, permanently removing them from the groundwater and reducing predicted radiation doses at the biosphere.

- More data are required to support modeling of the SZ, especially for the regional flow system between the repository and the accessible environment 20 to 30 km away. Key geologic, hydrologic, and geochemical data, including information about long-range colloid transport, have the potential to answer specific questions, such as the role of stratigraphy and structure, recharge and discharge locations, and possible ages of water. Obtaining these data is likely to improve the understanding of SZ characteristics much more than additional modeling efforts will.

- Current estimates of SZ dilution eventually may prove to be conservative, but supporting a larger dilution factor will be difficult unless new data are obtained to support the estimates produced by numerical models. The wells and experiments planned by Nye County should provide valuable information about the part of the SZ downgradient of Yucca Mountain. However, these wells may not provide sufficient data, and additional testing at other sites closer to Yucca Mountain may be needed.

Abbreviations and Acronyms

Board	U. S. Nuclear Waste Technical Review Board
CFR	Code of Federal Regulations
CFu	Crater Flat undifferentiated unit
CHn	Calico Hills nonwelded unit
^{36}Cl	chlorine-36
cm	centimeter
DOE	U.S. Department of Energy
EBS	engineered barrier system
ECRB	enhanced characterization of the repository block
ESF	Exploratory Studies Facility
HLW	high-level radioactive waste
km	kilometer
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
M&O	DOE's management and operating contractor
mm/yr	millimeters per year
MTU	metric ton of uranium
Np	neptunium
NRC	U.S. Nuclear Regulatory Commission
NWTRB	U.S. Nuclear Waste Technical Review Board
PCI	pellet-cladding interaction
PTn	Paintbrush Tuff nonwelded unit
SNF	spent nuclear fuel
SZ	saturated zone
SZEE	saturated zone expert elicitation
TCw	Tiva Canyon welded unit
TSw	Topopah Spring welded unit
TSPA	total system performance assessment
TSPA-VA	total system performance assessment-viability assessment
USGS	U.S. Geological Survey
UZ	unsaturated zone
UZFMEE	unsaturated zone flow model expert elicitation
VA	viability assessment
WPDEE	waste package degradation expert elicitation

References

D'Agnese, Frank A.; Claudia C. Faunt; A. Keith Turner; and Mary C. Hill. 1996. *Hydrogeologic Evaluation and Numerical Simulation of the Death Valley Regional Ground-Water Flow System, Nevada and California.* USGS Water-Resources Investigations Report 96-4300. Denver, Colorado: U.S. Geological Survey.

Andrews, R.W. 1998a. "Basic Structure, Conceptual Model, and Results of the TSPA-VA." Presentation to Nuclear Waste Technical Review Board's Panel on Performance Assessment. April 23, 1998. Albuquerque, New Mexico.

Andrews, R.W. 1998b. "Viability Assessment Total System Performance Assessment—Summary of Results and Sensitivity Analyses." Presentation to Nuclear Waste Technical Review Board. June 24, 1998. Las Vegas, Nevada.

Arnold, B.W. 1998. "Saturated Zone Flow and Transport Analyses in Total System Performance Assessment for Yucca Mountain." Presentation to Nuclear Waste Technical Review Board. January 20-21, 1998. Amargosa Valley, Nevada.

Barnard, Ralston W. 1998. "Analysis of Disturbed Events for TSPA-VA." Presentation to Nuclear Waste Technical Review Board's Panel on Performance Assessment. April 24, 1998. Albuquerque, New Mexico.

Barrett, Lake H. 1998. "Status of the Civilian Radioactive Waste Management Program." Presentation to Nuclear Waste Technical Review Board. May 18, 1998. Falls Church, Virginia.

Bodvarsson, G.S. 1996. "Conceptual Model of Flow in the Unsaturated Zone: New Insights." Presentation to Nuclear Waste Technical Review Board. October 9-10, 1996. Arlington, Virginia.

Bodvarsson, G.S.; T.M. Bandurraga; and Y.S. Wu, eds. 1997. *The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Assessment*. LBNL-40378. Berkeley, California: Lawrence Berkeley National Laboratory.

Civilian Radioactive Waste Management System. Management & Operating Contractor (M&O). 1995a. *Thermal Loading Study for FY 1995*. B00000000-01717-5705-00016. Las Vegas, Nevada: TRW Environmental Safety Systems, Inc.

——— 1995b. *Total-System Performance Assessment - 1995: An Evaluation of the Potential Yucca Mountain Repository*. B00000000-0717-2200-00099-Rev. 01. Las Vegas, Nevada: TRW Environmental Safety Systems, Inc.

——— 1996. *Emplaced Waste Package Structural Capability Through Time Report*. B00000000-01717-5705-00001 Rev 00. Las Vegas, Nevada: TRW Environmental Safety Systems, Inc.

——— 1997a. "Management Design Review, Presentation Materials." Presentation to Management. Las Vegas, Nevada. June 23-24, 1997.

——— 1997b. *Controlled Design Assumptions Document*. B00000000-01717-4600-00032, Rev. 04, ICN3, November 6, 1997. Las Vegas, Nevada: TRW Environmental Safety Systems, Inc.

——— 1998. *Constraints on Solubility-Limited Neptunium Concentrations for Use in Performance Assessment Analyses*. B00000000-01717-2200-00191, Rev. 00, January 23, 1997. Las Vegas, Nevada: TRW Environmental Safety Systems, Inc.

Cohon, Jared L. 1997. April 15 letter from Jared L. Cohon, Chairman, Nuclear Waste Technical Review Board, to April V. Gil, Yucca Mountain Site Characterization Office, transmitting comments on the proposed revisions to the Department of Energy's *General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories* (10 CFR 960).

Czarnecki, John B. 1989. "Characterization of the Subregional Ground-Water Flow System at Yucca Mountain and Vicinity, Nevada and California." *Radioactive Waste Management and the Nuclear Fuel Cycle.* Vol. 13, No. 1-4: pp. 51-61.

Danko, George. 1997. *Merits of Ventilation for the Proposed Repository at Yucca Mountain*. Review report submitted to Nuclear Waste Technical Review Board. June 1997. Reno, Nevada. Unpublished.

Dillon, C.P. 1998. "Behavior of Reactive Metals." *Materials Performance*. Vol. 37, No. 7 (July): p. 69.

Elsworth, Derek. 1998. "TM Drift Stability—Preliminary Evaluation." Presentation at Workshop on Preliminary Interpretations, Near-Field / Altered Zone Coupled Effects, Expert Elicitation Project. January 7, 1998. South San Francisco, California.

Fabryka-Martin, J.T., et al. 1997. *Evaluation of Flow and Transport Models of Yucca Mountain, Based on Chlorine-36 Studies for FY 97*. Los Alamos, New Mexico: Los Alamos National Laboratory.

Fabryka-Martin, J.T., et al. 1998. "Distribution of Fast Hydrologic Paths in the Unsaturated Zone at Yucca Mountain." Presentation at the 8th International High-Level Radioactive Waste Management Conference. May 11-14, 1998. Las Vegas, Nevada.

Flint, A.L. 1995. "Shallow Infiltration and the Initiation of Fracture Flow at Yucca Mountain Nevada." Presentation to Nuclear Waste Technical Review Board's Panel on Hydrogeology and Geochemistry. June 26-27, 1995. San Francisco, California.

Flint, A.L.; J.A. Hevesi; and L.E. Flint. 1996. *Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area, Nevada.* Milestone Report 3GUI623M. Denver, Colorado: U.S. Geological Survey.

Franklin, D.G. 1997. "The Corrosion of Zircaloy-Clad Fuel Assemblies in a Geologic Repository Environment." Presentation to Waste Form Expert Elicitation Panel. December 15, 1997. San Francisco, California.

Gdowski, Gregory E. 1995. *Activity Plan: Long-Term Corrosion Studies*. E-20-50 Revision 2. Livermore, California: Lawrence Livermore National Laboratory.

Geldon, A.L., et al. 1997. *Results of Hydraulic and Conservative Tracer Test in Miocene Tuffaceous Rocks at the C-Hole Complex, 1995 to 1997, Yucca Mountain, Nye County, Nevada*. Level 3 milestone SP23PM3. Denver, Colorado: U.S. Geological Survey.

Haynes International, Inc. 1997. *Hastelloy® C-22® Alloy. Haynes International Product Brochure H-2019E.* Kokomo, Indiana. (From bibliography in untitled secondary source.)

Hillner, E.; D.G. Franklin; and J.D. Smee. 1998. *The Corrosion of Zircaloy-Clad Fuel Assemblies in a Geologic Repository Environment*. WAPD-T-3173. West Mifflin, Pennsylvania: Bettis Atomic Power Laboratory.

Kersting, A.B.; D.K. Smith; D.W. Efurd; D.L. Finnegan; and J.L. Thompson. 1997. “Plutonium in Groundwater at the Nevada Test Site.” *Science* (Submitted).

McCright, R. Daniel. 1995. *Scientific Investigation Plan: Metal Barrier Selection and Testing*. SIP-CM-01 Revision 2. Livermore, California: Lawrence Livermore National Laboratory.

Macdonald, Digby D. 1992. “The Point Defect Model for the Passive State.” *J. Electrochem. Soc.* Vol. 139, No. 12: pp. 3434-3449.

McNeish, Jerry A. 1998a. “Waste Package Degradation.” Presentation to Nuclear Waste Technical Review Board’s Panel on Performance Assessment. April 23, 1998. Albuquerque, New Mexico.

——— 1998b. “Evaluation of EBS Processes: Near Field Geochemical Environment, Waste Form Degradation / Mobilization, EBS Transport.” Presentation to Nuclear Waste Technical Review Board’s Panel on Performance Assessment. April 24, 1998. Albuquerque, New Mexico.

Montazer, Parviz, and William E. Wilson. 1984. *Conceptual Hydrologic Model of Groundwater Flow in the Unsaturated Zone, Yucca Mountain, Nevada.* Water-Resources Investigations Report 84-4345. Lakewood, Colorado: U.S. Geological Survey.

Moyer, Thomas C.; Jeffrey K. Geslin; and Lorraine E. Flint. 1996. *Stratigraphic Relations and Hydrologic Properties of the Paintbrush Tuff Nonwelded (PTn) Hydrologic Unit, Yucca Mountain, Nevada*: Open-File Report 95-397. Denver, Colorado: U.S. Geological Survey.

National Research Council (NAS / NRC). Committee on Technical Bases for Yucca Mountain Standards. 1995. *Technical Bases for Yucca Mountain Standards.* Washington, D.C.: National Academy Press.

Nuclear Waste Technical Review Board (NWTRB). 1997. *Report to the U.S. Congress and the Secretary of Energy, January to December 1996.* Arlington, Virginia.

——— 1998a. *1997 Findings* and *Recommendations.* Arlington, Virginia.

——— 1998b. Waste Package Workshop. May 18-19, 1998. Falls Church, Virginia (transcript of proceedings). Arlington, Virginia.

Paces, J.B., et al. 1996. *Synthesis of Ground-Water Discharge Deposits Near Yucca Mountain*. Report 3GQH671M, final version. Denver, Colorado: U.S. Geological Survey.

Peterman, Z.E., and J.B. Paces. 1996. “Paleohydrology—Age Control from U-Series and Carbon-14 Dating of Calcite and Opal in the ESF.” Presentation to Nuclear Waste Technical Review Board. July 9-10, 1996. Denver, Colorado.

Roseboom, Eugene H., Jr. 1983. *Disposal of High-Level Nuclear Waste Above the Water Table in Arid Regions*: Circular 903. Alexandria, Virginia: U.S. Geological Survey.

Roy, A.K.; D.L. Fleming; and B.Y. Lum. 1997. *Electrochemical and Metallographic Evaluation of Alloy C-22 and 625*. UCRL-ID-127355. Livermore, California: Lawrence Livermore National Laboratory. (From bibliography in untitled secondary source.)

Sassani, David C.; Paul Domski; Annemarie Meike; and William Glassley. 1997. “Near-Field Geochemical Environment: Potential In-Drift Gas and Water Compositions.” Presentation to Waste Form Expert Elicitation Panel. San Francisco, California. December 15, 1997.

Sassani, David C., and Eric Siegmann. 1998. *Constraints on Solubility-Limited Neptunium Concentrations for Use in Performance Assessment Analyses.* January 23, 1998. B00000000-01717-2200-00191, Rev. 00. Las Vegas, Nevada: TRW environmental Safety Systems, Inc.

Saturated Zone Expert Elicitation Panel (SZEE). 1997. *Saturated Zone Flow Model Expert Elicitation Project, Final Report.* Las Vegas, Nevada: TRW.

Sevougian, S.David, et al. 1995. “Unsaturated- and Saturated-Zone Flow and Transport,” Chapter 7 in *Total System Performance Assessment-1995: An Evaluation of the Potential Yucca Mountain Repository.* Las Vegas, Nevada: TRW Environmental Safety Systems, Inc.

Siegmann, Eric. 1997. “Cladding Credit in TSPA-VA.” Presentation to Waste Form Expert Elicitation Panel. November 19, 1997. San Francisco, California.

Simmons, A.M., and G.S. Bodvarsson. 1997. *Building Confidence in Thermohydrologic Models of Yucca Mountain Using Geothermal Analogues.* Berkeley, California: Lawrence Berkeley National Laboratory.

Stacey, Devin; Jayant Bondre; Michael Bryson; John Kessler; and Martin Pytel. 1997. *Assessment of Thermal Loading Strategies for the Yucca Mountain Site.* TR-108537. Palo Alto, California: Electric Power Research Institute.

Stahl, David. 1997. “Materials Research Program: Status and Changes.” Presentation to Nuclear Waste Technical Review Board. October 23, 1997. Fairfax, Virginia.

U.S. Congress. 1996. *Energy and Water Development Appropriations Act, 1997.* 104th Congress, 2nd Session. Washington, D.C.: Government Printing Office.

U.S. Department of Energy. Office of Civilian Radioactive Waste Management. 1988. *Site Characterization Plan. Overview.* Washington, D.C.

——— 1998. *Repository Safety Strategy*: *U.S. Department of Energy’s Strategy to Protect Public Health and Safety After Closure of a Yucca Mountain Repository*. Revision 1. Washington, D.C.

Unsaturated Zone Flow Model Expert Elicitation (UZFMEE) Panel. 1997. *Unsaturated Zone Flow Model Expert Elicitation Project: May 1997.* San Francisco, California: Geomatrix Consultants.

Waste Package Degradation Expert Elicitation (WPDEE) Project Panel 1998. *Waste Package Degradation Expert Elicitation Project, Rev. 1.* San Francisco, California: Geomatrix Consultants, Inc.

Whipple, C.; R. Budnitz; R. Ewing; D. Moeller; J. Payer; and P. Witherspoon. 1998. *Third Interim Report, Total System Performance Assessment Peer Review Panel*, prepared for Civilian Radioactive Waste Management and Operating Contractor. June 25, 1998. Las Vegas, Nevada.

Winograd, I.J. 1981. “Radioactive Waste Disposal in Thick Unsaturated Zones.” *Science*, v. 212, no. 4502: pp. 1457-1464.

Wolery, Thomas J., and Stephanie A. Daveler. 1992. *EQ6, A Computer Program for Reaction Path Modeling of Aqueous Geochemical Systems: Theoretical Manual, User’s Guide, and Related Documentation*. Version 7.0. UCRL-MA-110662 Pt. IV. Livermore, California: Lawrence Livermore National Laboratory.

10 CFR 60 (*Code of Federal Regulations)* Title 10, *Energy*, Part 60. “Disposal of High-Level Radioactive Waste in Geologic Repositories.” Washington, D.C.: U.S. Government Printing Office.