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.

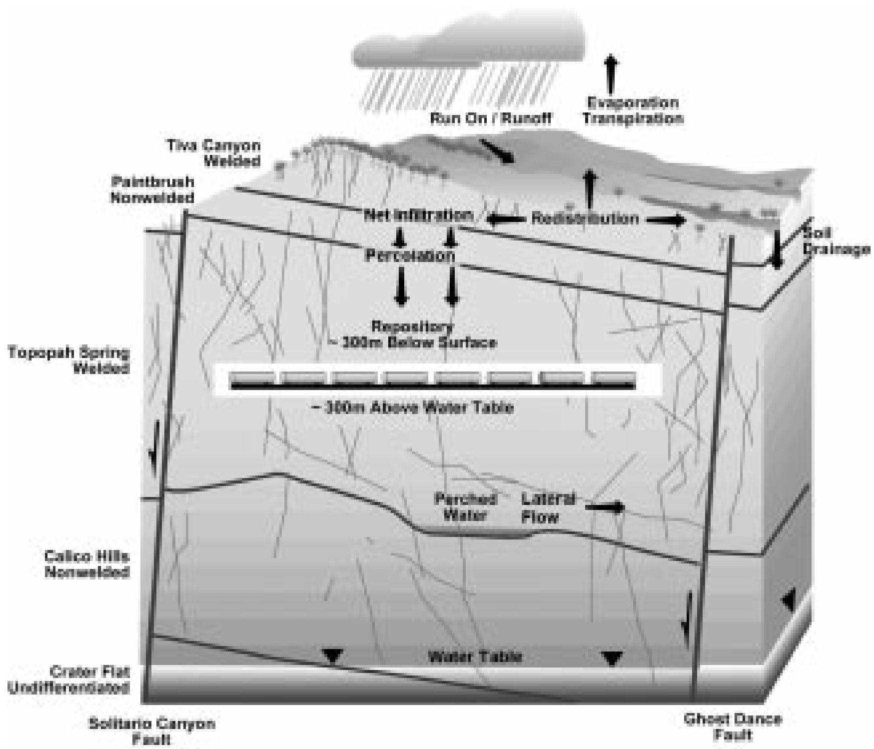
In this report, the Board evaluates information about the proposed repository presented to it in meetings and other exchanges, with emphasis on the unsaturated zone[2] (UZ), the engineered barrier system[3] (EBS), and the saturated zone[4] (SZ). The Board considers and comments on some of the important 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.

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.

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

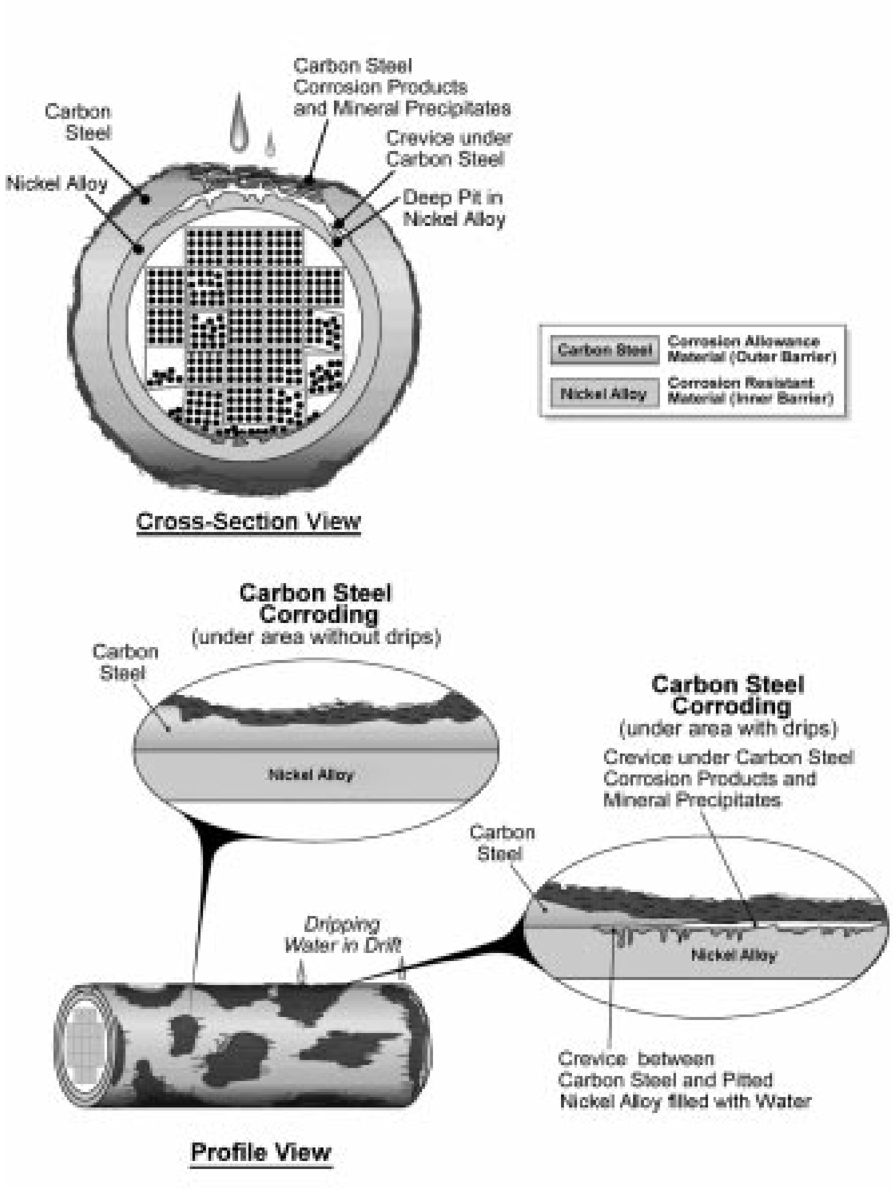


I. The Repository as a System

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.

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



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.

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.

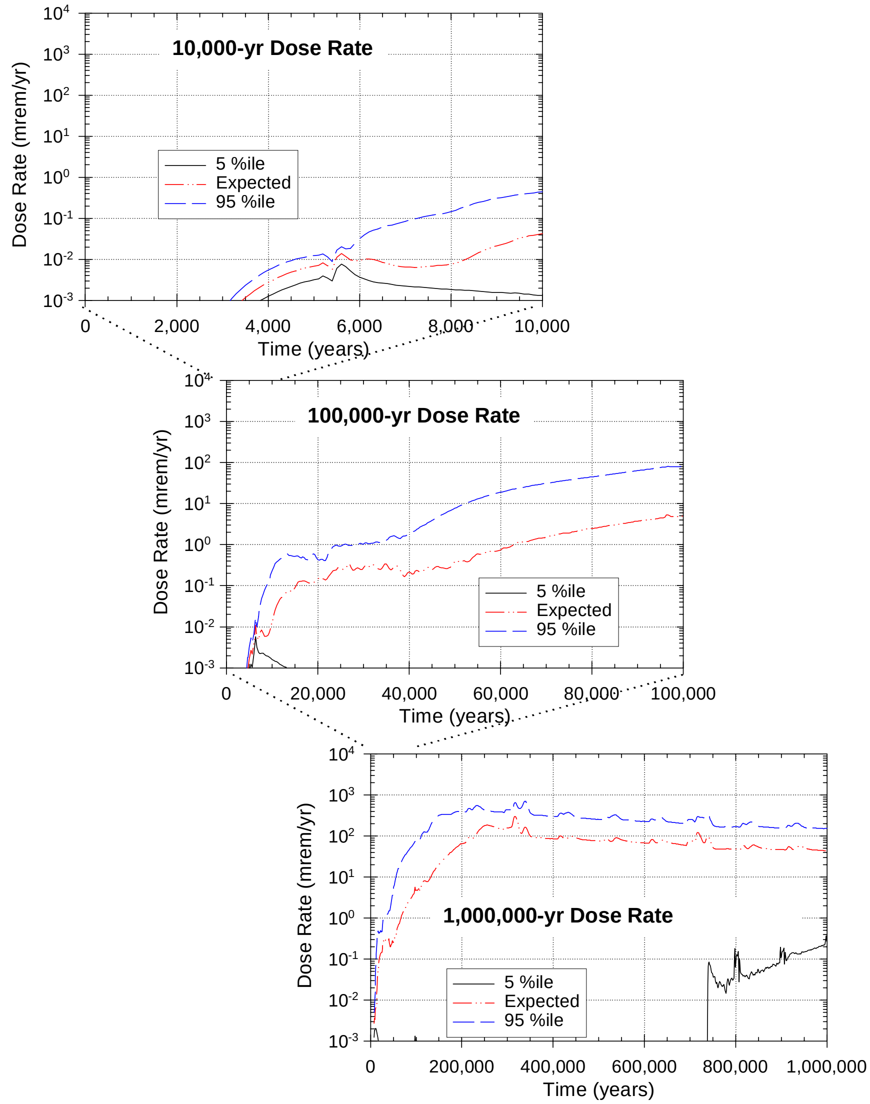
II. Features Affecting Repository Performance

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.

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.

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



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.

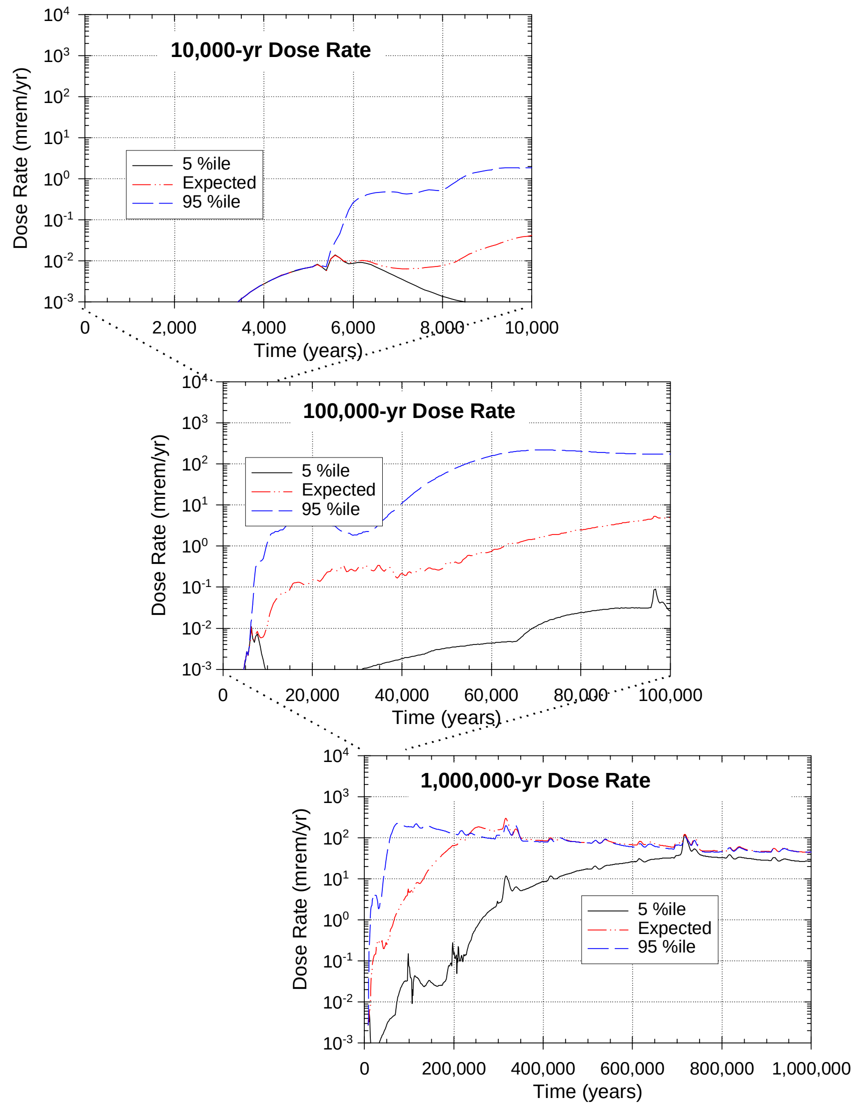
11. "Alloy 22" (UNS N06022) is a generic term for C-22, which is the trade name of a specific manufacturer.

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

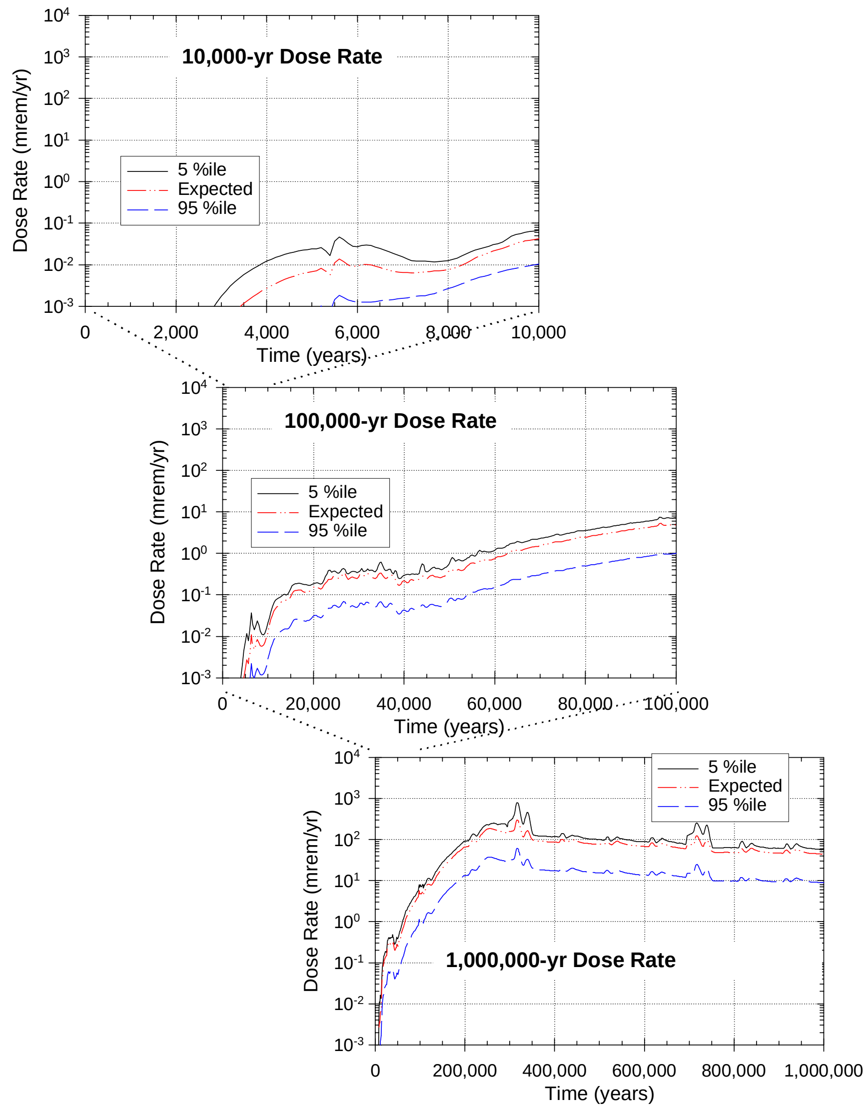
Additional SZ flow-and-transport data, both on the regional scale and the site scale, are needed. Regional hydrologic and stratigraphic data between Yucca Mountain and Amargosa Valley and other potential discharge points are nearly absent at present. This groundwater-flow domain is dominated by networks 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.

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



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.

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.