Chapter 1
Board Oversight of the DOE's Scientific and Technical Activities at Yucca Mountain

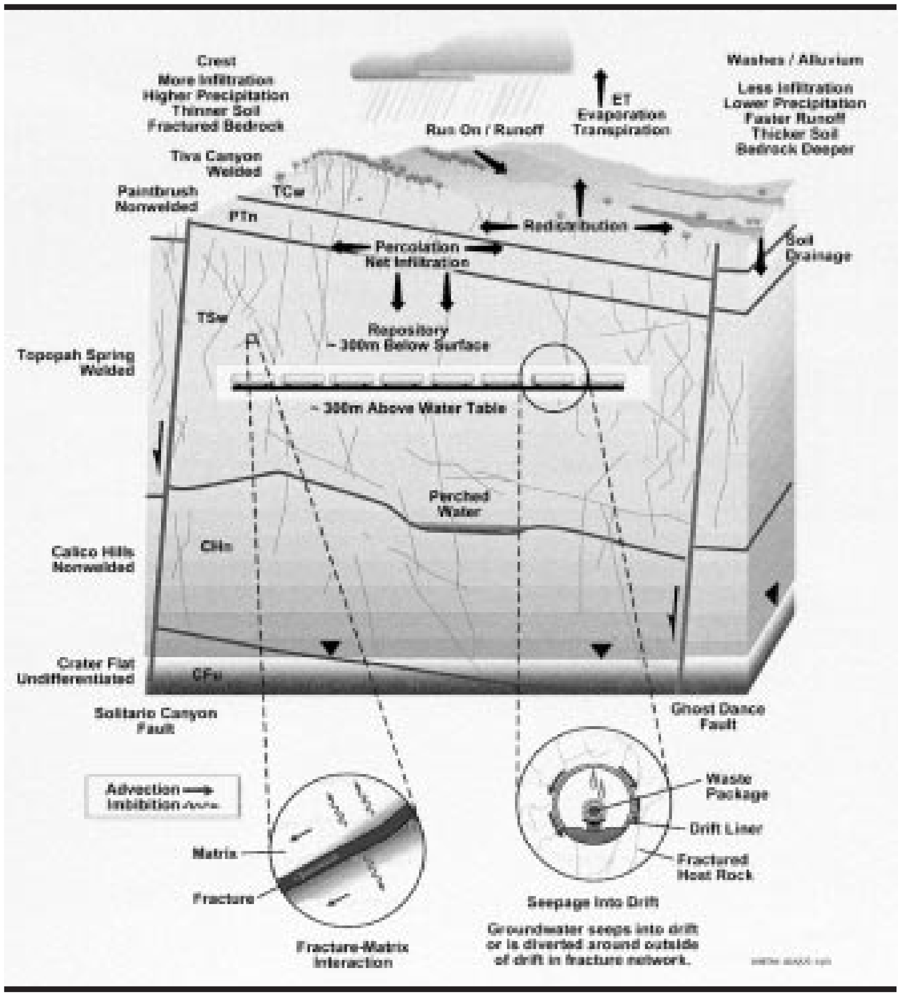
The DOE is characterizing Yucca Mountain in Nevada to evaluate the suitability of the site for constructing a mined geologic repository for the permanent disposal of spent nuclear fuel and high-level radioactive waste. It also is preparing designs for the packages in which the waste will be disposed of and the subsurface repository facilities. During 1998, the full Board reviewed those activities at its meetings. In addition, individual Board members attended DOE workshops and traveled to Yucca Mountain.

I. Characterization of the Unsaturated Zone

A. Overview

If the Nuclear Regulatory Commission (NRC) authorizes the repository, it will be constructed in the unsaturated zone (UZ) in welded tuff (volcanic rock) at a depth of at least 300 meters below the land surface and a distance of approximately 300 meters above the regional water table. (See Figure 1-1.) The UZ at Yucca Mountain is a critical natural feature of the repository system. Along with structural integrity, the UZ will provide the hydrologic and chemical environment for the waste canisters. The UZ will be the medium through which the radionuclides will be transported with the percolating water to the

Figure 1–1. Cross Section of Yucca Mountain (adapted from Andrews 1998)



saturated zone. The predicted repository performance is critically dependent on the volume and geochemistry of the water that may reach waste packages, mobilize the waste, and carry radionuclides to the water table. The potential repository block consists of a fault-bounded structural block composed of alternating welded and nonwelded tuffs of the mid-Miocene Age, about 10 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 evident at land surface may be present within the block. Largely according to the degree of welding, the tuffs within the UZ at Yucca Mountain are grouped informally into hydrogeologic units that, from the surface down, are termed 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 level of the potential repository consists of densely welded ash-flow tuff within the TSw unit.

B. The DOE's Scientific and Technical Work

The DOE focused its scientific research in 1998 on addressing the following key UZ uncertainties: (1) the amount of water that potentially could seep into the emplacement drifts, (2) thermally induced flow in the UZ, and (3) transport of radionuclides through the UZ.

1. Seepage Flux

Of the natural characteristics of Yucca Mountain that are crucial for predicting repository performance, seepage flux—the magnitude and distribution of the percolating water that seeps (drips) into the emplacement drifts and, potentially, onto the waste packages—is the most important. This is because the amount, timing, and chemistry of water entering the tunnels can have a significant effect on the environment of the waste packages and other engineered barriers. Seepage flux also is an important determinant of the rate at which radionuclides can be mobilized from the waste form and released from the repository. Assessing the performance of the potential repository requires not only that the current level of seepage flux be estimated, but also that future levels be considered because the flux is expected to increase as the climate becomes wetter.

The estimates of this fraction for the present climate and for future climates are derived from model computations. The computations, although informative, are based on geologic and hydrologic parameters that cannot be estimated with certainty. During 1998, several experiments and tests were begun in the Exploratory Studies Facility (ESF) (e.g., alcove 1 and other locations) to measure the movement of water through the UZ under controlled flow conditions at multiple scales and to measure the seepage of water into excavated areas. In addition, experiments were designed to determine the movement of water from the cross drift to the ESF. The majority of these tests are in the initial scoping stages, and much of the key data are scheduled to be collected in calendar year 1999.

Results from monitoring ambient moisture conditions in the ESF and in various alcoves were obtained in 1998. One finding is the significant differences between the measurements of ambient water potential taken in the ESF tunnel and the values inferred from laboratory experiments on cores taken in the rocks from the horizon of the proposed repository (TSw). The TSw appears wetter than previously thought—that is, the pores, or voids, in the nonlithophysal TSw may be closer to 90 percent saturated than to 80 percent saturated.[2] These data could have as-yet-undetermined implications of matrix-fracture interactions and flow in the UZ and seepage rate into the repository drift.

2. Thermally Induced Flow in the UZ

A repository with a high thermal load (temperatures higher than about 100°C)[3] is designed to drive water away from waste packages for the first 3,000 years. However, research has shown that a high thermal load may result in additional water movement around, and perhaps into, the emplacement drifts

2. The differences are most likely due to an improvement in sampling techniques that minimizes the drying-out influence of forced-air drift ventilation. The problem associated with the previous sampling techniques was pointed out by Dr. Gaylon Campbell at the Board's June 1997 meeting.

during the early high-temperature regime. To understand this thermally induced flow better, the DOE has conducted single-heater and drift-scale heater experiments.

The single-heater test was completed in 1997 and has produced useful information on the movement of water and on the dryout region, which is formed around the heater. The drift-scale heater test, which began on December 6, 1997, is designed to provide a similar type of data but on a much larger spatial scale and for a longer time. The heating cycle is anticipated to last approximately 4 years. The cooling phase of the experiment also will take approximately 4 years so that there is sufficient time for chemical and mechanical processes that may alter near-field rock properties.

3. Transport of Radionuclides in the UZ

In 1998, the DOE began conducting experiments at Busted Butte to better characterize the flow and transport of radionuclides in the UZ after release of radionuclides from waste packages begins. These experiments are designed to investigate the transport properties of reactive and nonreactive tracers in the vitric tuffs in the Calico Hills Formation. Special emphasis will be on the retardation potential of the vitric tuffs and the likelihood of colloidal transport through this unit. The testing will be conducted in several phases and at several scales. The phases were designed for observing and measuring the movement of water and various tracers under controlled conditions through well-defined units. The tracers were chosen to represent various sorptive and diffusion properties that could be used in transport modeling.

The DOE continued its assessment of the solubility of neptunium (Np). The solubility of Np is important because the isotope ^{237}Np is a major contributor to the calculated radiation dose at 10,000 years and beyond. The initial volume of ^{237}Np (half life of 2.14×10^6 years) in spent nuclear fuel is approximately 0.03 percent of the initial inventory of radionuclides at the time of emplacement. The concentration increases with time as ^{237}Np is produced by the decay of americium-241 (half life of 432.7 years).

The DOE believed that the earlier (TSPA-95) solubility estimates (CRWMS 1995b) were too high (CRWMS 1998). The DOE concluded that its revised estimates of solubility represent a more realistic model of the situation that would exist in the proposed Yucca Mountain repository.[4]

As a result of the reassessment of experimental data, supported by thermodynamic calculations, the expected value for the solubility of Np in the VA is two orders of magnitude lower than the number used in TSPA-95. The new solubility values consequently lowers the calculated long-term potential dose that is due to Np by two orders of magnitude.

The DOE undertook field studies to better understand colloidal transport.[5] Strongly sorbing radionuclides, such as plutonium, may sorb on naturally occurring colloids in groundwater and migrate at velocities similar to the velocity of groundwater flow. This process can lead to travel times that are much shorter 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 (Kersting et al. 1999). The plutonium's origin was the 1968 nuclear test BENHAM on Pahute Mesa. All of the plutonium detected was associated with colloidal components, primarily clays and zeolites.

C. The Board's Review Activities

1. Seepage Flux

Most of the work on seepage flux that is being carried out in the ESF was reviewed by the Board during its visit to the tunnel on December 8, 1998. The

3. Throughout this chapter, the current design (reference design) of the underground facility is referred to as the "hot" repository design to distinguish it from a low-temperature alternative repository design.
4. The DOE initially reached this conclusion on the basis of experiments that used highly supersaturated solutions. The DOE's reassessment 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 reassessment, thermodynamic calculations of the solubility of Np also were performed.
5. A colloid is a particle that can be suspended easily or is a suspension of very fine particles.

Board was pleased to see the progress made and the magnitude of data that will be gathered on seepage flux in the next few years. In particular, the Board looks forward to reviewing the chlorine-36 (^{36}Cl) data that will be collected in the east-west drift as well as the data that will be collected on seepage between the east-west drift and the ESF.

The Board repeatedly has emphasized the importance of collecting data on ^{36}Cl and other environmental isotopes. Evidence of bomb-pulse ^{36}Cl has been well documented over the last few years and was reviewed by an outside panel at DOE's request in 1998.[6] The presence of bomb-pulse ^{36}Cl is the clearest evidence of rapid movement of water from the surface to depth at Yucca Mountain. Still, important questions remain about the significance of the data to overall flow and transport in the UZ. Quantitatively, how significant is this rapid-flow component? How is this flow distributed in time and space? Is this flow associated with major faults and fractures and thus can it be identified spatially? Although the Board has been given preliminary answers to these questions, they are not fully resolved.

2. Thermally Induced Flow in the UZ

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.

Because mathematical models sometimes smooth or average, they may 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 in bypass around an emplacement tunnel and that a local dryout 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 realistically predicting how much water could enter the tunnels when repository temperatures are high.

Currently, the question of how much water will be entering the tunnels during the thermal episode has not been answered by model computations or experiments. The single-heater test has provided useful information on the movement of water. 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.

3. Transport of Radionuclides in the UZ

On several occasions in 1998, the Board visited the Busted Butte facility, where the flow and tracer experiments are being performed. The design and construction of the facility and the development of the testing plan moved rapidly over the course of the year. As data are produced from the Busted Butte studies, the Board will evaluate their validity and significance.

Despite the substantial effort that has gone into the reassessment 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 spent nuclear fuel been characterized adequately? Each question is discussed below.

The first question deals with the use of proper conceptual models. The DOE's reassessment of the experimental data, as well as the computer simulations, assumes that the Np-bearing spent nuclear fuel dissolves in a water-saturated system. In other words, the use of data from a state of undersaturation assumes that the spent nuclear fuel will dissolve directly into water and then move out of the repository. The primary Np-bearing solid phases in the spent nuclear fuel will control the solubility of Np in the migrating water. This is the initial conceptual model.

6. Because of the significance of bomb-pulse ^{36}Cl, the Board's understanding is that the DOE plans additional tests to verify its presence.

A different conceptual model would assume that (1) the primary Np-bearing solid phases dissolve into water in a partially saturated system and that (2) secondary Np-bearing minerals then precipitate from that water. 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. The secondary Np-bearing minerals then could be redissolved at a later time. 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 spent nuclear fuel. 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 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 spent nuclear fuel. The recent reevaluation of the solubility of Np assumes that the controlling solid form in the spent nuclear fuel is NpO_2. However, nonstoichiometric forms of Np-oxygen compounds also may exist in the spent nuclear fuel, and they conceivably could control the solubility of Np. Metallic forms of Np, rather than NpO_2, may exist in the spent nuclear fuel, 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 sum, the remaining questions about the conceptual model and about 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. Thus, acknowledging a very broad range of uncertainty about Np solubility would be prudent.

The observations made at the Nevada Test Site and laboratory experiments indicate that colloidal transport of plutonium cannot be ignored and can contribute to the transport of strongly sorbing radionuclides, potentially increasing the dose at the accessible environment. The DOE will have to gather data, such as the reversibility of sorption on colloids and colloid stability, to estimate or bound the importance of colloidal transport.

D. The Board's Conclusions

The UZ of Yucca Mountain may potentially be shown to be 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.

- Seepage flux under ambient conditions can be 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 experimentally, but planned experiments may produce relevant data.

- The effects of repository heat on thermohydrologic conditions near the repository are not well understood. Tests that have been initiated at Yucca Mountain must be completed to improve understanding and reduce uncertainties. However, their results will not be fully available for 7 more years.

- The testing at Busted Butte is being conducted to assess the transport of colloids and other aqueous species through the UZ below the repository. If successful, the tests could provide information for reducing uncertainty in these areas.

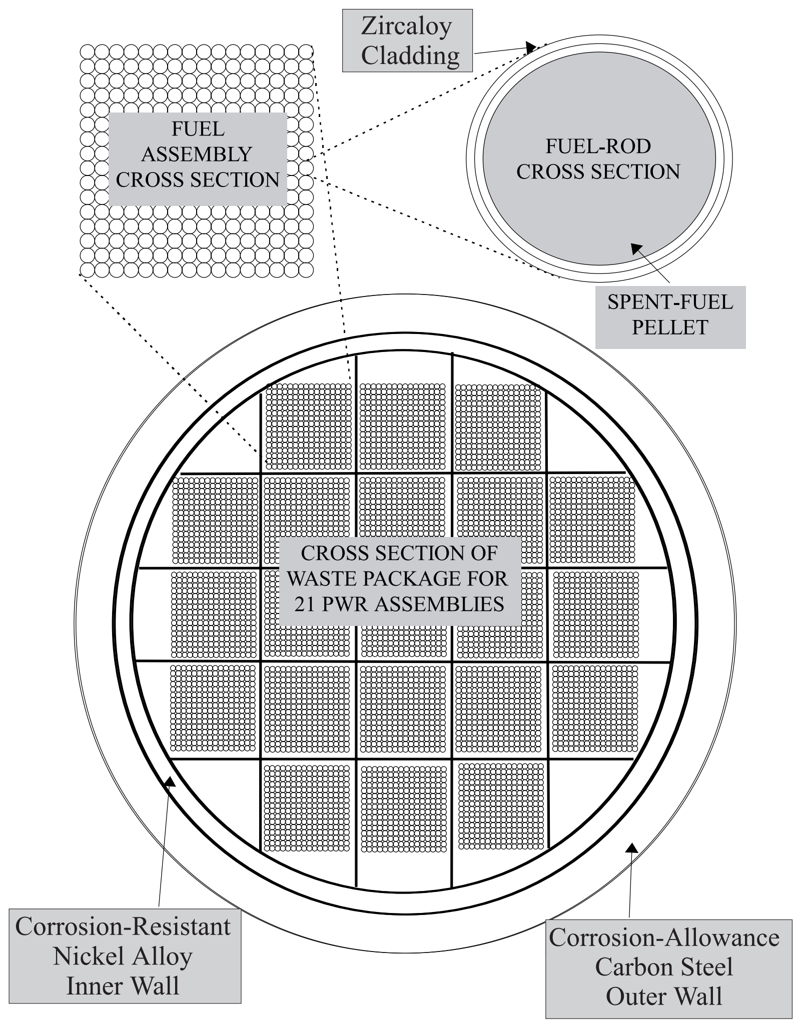
- Despite recent progress in reevaluating the solubility of Np, significant uncertainties (possibly as much as five orders of magnitude) remain. Because the long-range dose potential of ^{237}Np is so significant, additional effort is needed to narrow these large uncertainties.

II. Waste Package Design

A. Overview

According to regulations, "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). That is, the term includes not only the waste container but also its contents. In the reference design, a waste package containing spent commercial fuel[7] will have at least four distinct barriers that contribute to defense-in-depth: (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 containing fission products and actinides. In general, the processes leading to failure of an inner barrier would not begin until the barrier immediately outside of it is penetrated (see Figure 1-2).

Figure 1-2. Cross Section of 21-PWR Spent-Fuel Waste Package



Waste packages emplaced in an underground facility at Yucca Mountain will undergo a range of external environmental conditions that will affect the rate of corrosion of the packages. The range of external environmental conditions (pressures, temperatures, and the chemical compositions of the near-field gases, liquids, and solids before they contact the waste packages) is reasonably well bracketed.

Predicting corrosion with reasonable confidence, however, 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, corrosion products, radiation, and external environmental conditions. The modified environmental conditions on or in 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. TSPA-VA indicates that for the reference design, the nickel-alloy inner wall and the zircaloy cladding are by far more important barriers than the carbon-steel outer wall. Therefore, the discussion below is limited to these two barriers.

7. On the basis of radioactivity, spent fuel will comprise well over 90 percent of the waste to be disposed of at the proposed Yucca Mountain repository.

1. Nickel-Alloy Inner Wall

The material for the inner wall is a chromium-rich nickel-base alloy with the designation Alloy 22.[8] The corrosion resistance of the alloy is due to a microscopically thin passive film on the surface of the alloy that separates the alloy from the surrounding environment. Research has shown that passivity can be compromised under certain severe conditions, even for highly corrosion-resistant alloys, such as Alloy 22, and that rapid corrosion follows when passivity is compromised. Research also has shown that those alloys remain protected by passive layers under less severe conditions and thus have extremely low corrosion rates.

Combinations of ferric and chloride ions[9] in water are known to generate low-pH oxidizing environments that cause passivity breakdown in corrosion-resistant alloys. Conceivably, these ionic combinations could result from the presence of iron-corrosion products (e.g., from corrosion of the carbon-steel outer layer) and chloride ions concentrated by evaporation of seepage water. However, partly because of lack of long-term direct experience and partly because of uncertainties about the severity of the 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 among materials experts.

Even in the absence of ferric ion sources, localized attack of the passive layer protecting high-performance alloys can occur through pitting or crevice corrosion if aggressive microenvironments form at the surface of the passive layer. 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,[10] which could affect the zone of the final closure weld of the package or other regions of unrelieved stresses. Information available to date 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 involving ferric and chloride ions noted earlier.

Future research may prove that the environment immediately next to the metal surface will be only moderately aggressive. In that case, present understanding of corrosion phenomena (based on short-term investigations) indicates that the nickel-alloy wall should remain passive and corrode at a very slow rate. However, Alloy 22 and related 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. Historical experience with any alloy relying on passivity for corrosion protection also is relatively short. How stable the passive layers will remain, even in benign surroundings, over the extremely long repository time scale is a vital question.

2. Zircaloy Cladding

Like nickel-based alloys, zirconium alloys depend on the formation and stability of passive films for protection against corrosion. Titanium alloys, which are under consideration as an alternative waste package material and as a drip shield material, also rely on passivity for adequate performance. Although data on general corrosion of zircaloy cladding are extensive, they are mostly at conditions within nuclear reactors—conditions significantly different from, but not necessarily more severe than, some of the more extreme conditions that the cladding could be exposed to in a repository at Yucca Mountain. As is the case for nickel-based and titanium alloys, the environments formed by the combined interactions of corrosion products, radiolysis, pore water, and elevated temperatures need to be determined for cladding, as do the effects of these environments on the cladding.

8. The nominal composition of Alloy 22, in weight percent, is Ni 56, Cr 22, Mo 13, Co 2.5, W 3, and Fe 3.
9. Ferric ion [Fe(III)] hydrolyzes readily. A solution of the salt of any ferric ion and any of a number of anions (e.g., chloride) in pure water will be acidic and oxidizing. The same is true for Ni(IV) and Cr(VI) ions.
10. Stress-corrosion cracking is a cracking process that requires the simultaneous action of a corrosion mechanism and sustained tensile stress.

Zircaloy cladding clearly is an egress barrier, and it may well be a significant one. In TSPA-VA, the corrosion rates assumed for zircaloy were significantly lower than those used for Alloy 22. Quantifying the contribution of cladding to performance is difficult because (1) a small fraction of the cladding fails 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 attack from aggressive chemicals resulting from the radiolysis of water and 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 potential for degradation of cladding by mechanical forces after a waste package is breached; (6) essentially no data exist on the extent of localized corrosion of zircaloy under Yucca Mountain conditions; and (7) long-term zircaloy performance depends on extrapolation of short-term data for very long periods.

B. The DOE's Scientific and Technical Work

Experimental work supporting the waste package development program continued in 1998. Much of the experimental work in corrosion was carried out at Lawrence Livermore National Laboratory. A large and important part of the experimental work in corrosion research is the Long Term Materials Testing Program, which utilizes temperature-controlled vats partially filled with water containing dissolved minerals at concentrations that might be encountered by waste packages emplaced in Yucca Mountain. Samples of metals that are candidates for use underground at Yucca Mountain reside in the vats below, at, and above the waterline. The first samples were placed in some of the vats in September 1996. Periodically, samples are removed to ascertain the degree of corrosion. Most samples of corrosion-resistant materials were not among the first batches of samples placed in the vats, so data on these materials are limited.

During the last half of 1998, several additions were made to the corrosion research program. The additions appear to have come about partly as a result of the Board's Waste Package Workshop (NWTRB 1998d) and the Advisory Committee on Nuclear Waste's June 1998 working group meeting on near-field environment and engineered barriers.[11] All additions are short-term experiments, studies, or modeling exercises aimed primarily at achieving better understanding of localized corrosion (e.g., stress-corrosion cracking and crevice corrosion) of Alloy 22, titanium alloys, and other corrosion-resistant materials.

The results so far of the DOE's corrosion testing program indicate that corrosion rates are very low for candidate corrosion-resistant waste-package materials, consistent with predictions. The tests are scheduled to continue for at least the next several years. In general, the longer the tests continue, the greater the confidence in the results and the greater the confidence that unanticipated corrosion mechanisms having prolonged incubation periods do not exist. Thus, continuing the testing well into the "performance confirmation" period is important.[12]

C. The Board's Review Activities

The Board's review activities for the waste package in 1998 consisted primarily of (1) organizing and conducting the Waste Package Workshop in May, (2) reviewing progress in waste package and waste form modeling for TSPA-VA, and (3) attending the final waste package and waste form expert elicitation workshops and reviewing the subsequent final reports from the expert elicitations (Geomatrix 1998).

The final report from the waste form expert elicitation provided little support for taking a significant amount of cladding credit. One expert even indicated

11. The Board's Waste Package Workshop is discussed elsewhere in this document. Issues and recommendations from the June 1998 meeting of the Advisory Committee on Nuclear Waste are in Garrick 1998.

12. "Performance confirmation" means the program of tests, experiments, and analyses that is conducted to evaluate the accuracy and adequacy of the information used to determine with reasonable assurance that the performance objectives for the period after permanent closure will be met. The performance confirmation program starts during site characterization and continues until permanent closure. [10CFR60.2 and 10CFR60.140(b)]

that cladding credit probably could never be taken because of the large uncertainties in the environmental conditions surrounding the cladding. Despite these objections, the DOE took full cladding credit in the TSPA-VA. The Board is concerned that the DOE seemingly ignored the judgments of its own experts on this issue.

D. The Board's Conclusions

On the basis of its review of the DOE's scientific and technical investigations, the Board has reached the following conclusion about the current state of knowledge with respect to waste package design.

- Predicting the performance of a waste package design is a matter of predicting the external near-field environment surrounding 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 modified 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 should 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 (e.g., zircaloy, Alloy-22, and titanium) and on data gained during only the last year or so for Alloy 22 under Yucca Mountain-simulated conditions. Therefore, results from ongoing and planned research on corrosion of waste package materials will be essential to establishing the technical parameters of the design.

III. Repository Design

A. Overview

The reference design of the underground facility is based on 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] per acre). This 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 area under Yucca Mountain nominally bounded by the Ghost Dance fault on the east and the Solitario Canyon fault on the west. The reference design of the underground facility results in peak temperatures of nearly 200°C in the tunnel (drift) walls and 250°C on a waste package's outer surfaces.

In the VA design, the waste-emplacement tunnels are lined with precast-concrete floor and ground-support segments. Ventilation is provided by the north and south access ramps and two shafts connecting to a central 7.62-meter-diameter north-south exhaust tunnel below the underground facility. This system is ducted to the center of each waste-emplacement tunnel. The ventilation system provides separate air-flow systems for simultaneous emplacement of waste in completed emplacement tunnels and for construction of additional tunnels. In this hot repository design, each emplacement tunnel would be closed after it is filled, and ventilation of the closed tunnel would be reduced to a very low rate until repository closure.

The ambient temperature of the underground facility host rock at Yucca Mountain is approximately 25°C. If the average temperature of a waste-emplacement tunnel rises to 160°C (CRWMS 1997a), modeling indicates that the tunnel could expand vertically 8 to 10 mm while shrinking horizontally the same amount

(Elsworth 1998). These heat-induced deformations could increase the probability of rockfalls in the long term, possibly leading to localized tunnel collapse.[13]

Rockfalls make predicting the flow pattern and the amount of water contacting a waste package more difficult. The rockfalls would affect the local characteristics of the rock in the tunnel roof, making seepage flux more uncertain. Depending on the size and distribution of the rock fragments, localized tunnel collapse could create a zone of rock fragments around the waste package that could draw water toward the waste package in quantities far in excess of seepage flux predictions, or a collapse could create a region in which the water is dispersed around the waste package that could reduce the quantity of water contacting the waste package.

Tunnel stability also is important for waste package performance. For example, tunnel debris on a package surface may promote localized corrosion, which could shorten the life of a waste package. In addition, rocks falling from the roof of a tunnel could break through the wall(s) of a waste package already thinned by corrosion. For example, 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).

In the hot repository design, rock temperatures would peak about 50 years after waste is emplaced. If closure of the underground facility were delayed for about 300 years, the temperatures of the tunnels would have decreased to around 120°C and the rock would have passed through its period of maximum thermal response. By then, if the rock were still stable, it likely would remain stable indefinitely, barring significant seismic activity. If it has failed, repairs might be possible before closure of the underground facility.

B. The DOE's Scientific and Technical Work

1. Design Work

The DOE's management and operating contractor (M&O) continued to refine the reference repository design. The design is being altered so that the repository can be developed incrementally. In addition, design studies continued to address the problem of silica dust generation, which arose during excavation of the ESF.

At the June Board meeting, the M&O reported on plans for a major alternative repository design study, which is scheduled to produce a preferred repository design by mid-1999. The design will be developed for use in the license application to the NRC in 2002.

2. Tunnel Stability Workshop

A workshop on tunnel stability, sponsored by the DOE, was organized by the M&O's repository design group in December. A panel of seven geotechnical specialists was taken on a field trip to Yucca Mountain to view the geologic strata in which the repository would be built. The visit was followed by a series of presentations by the repository designers on the current repository design.

The morning was spent reviewing the geology of the repository horizon and hearing a presentation on the layout and details of the VA repository design. The afternoon consisted of a tour of the ESF and the east-west drift. On the following day, the repository designers made presentations on the repository layout, ground-support designs and analyses, key-block analyses of several geologic zones constituting the repository block, rock properties, and seismic analysis of drifts. The alternative design studies were discussed briefly.

The presentations were limited to the repository preclosure period and were oriented toward analysis of the VA repository design. There was no discussion of postclosure (i.e., long-term) drift stability or the effects of the thermal pulse on long-term drift

13. Localized tunnel collapse may be thought of as a progression of many rockfalls until the tunnel is filled with rock particles of various sizes and no further collapse can occur.

stability. Information that had been sent to the panelists ahead of time was focused only on the VA ground-support design. The questions were posed: "Is this lining design satisfactory? If not, then why not, and what would be satisfactory?"

The focus was limited to the middle nonlithophysal rock properties as opposed to the lower lithophysal, which is where 70 percent of the repository would be located. The M&O has operated on the assumption that concrete liners are needed to provide support until repository closure and that repository design considerations end at closure. The designers have not considered the effects of geologic heterogeneities, differences in the properties of the rock strata, or the excavation-damage zone created by different types of excavation equipment.

Preliminary comments from the panelists indicated that repository ground support for waste emplacement drifts could be provided by rock bolts and wire mesh, which are needed for operational and worker safety. Rock-failure mode will be through localized raveling (i.e., progressive small-rock fallout).

C. The Board's Review Activities

During 1998, the Board focused its efforts on encouraging the DOE to examine a range of alternative repository designs and conduct trade-off analyses before selecting any one of them.[14] Although the DOE had to adopt a "reference design" early in the VA process and believed that it could not undertake a comprehensive assessment of alternative designs at the same time that it was preparing the VA, the DOE made a commitment to the Board that it would seriously explore other designs before taking one forward into the site-suitability process.[15]

D. The Board's Conclusions

On the basis of its review of the reference design, the Board reaffirms the conclusion it reached in its report to the U.S. Congress and the Secretary of Energy (NWTRB 1998a):

- 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, mechanical, and chemical changes in the rock surrounding tunnels and could reduce the rates of waste package corrosion and radionuclide mobilization from the waste.

IV. Characterization of the Saturated Zone

A. Overview

The SZ at Yucca Mountain lies at depths of 500 or more 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 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.

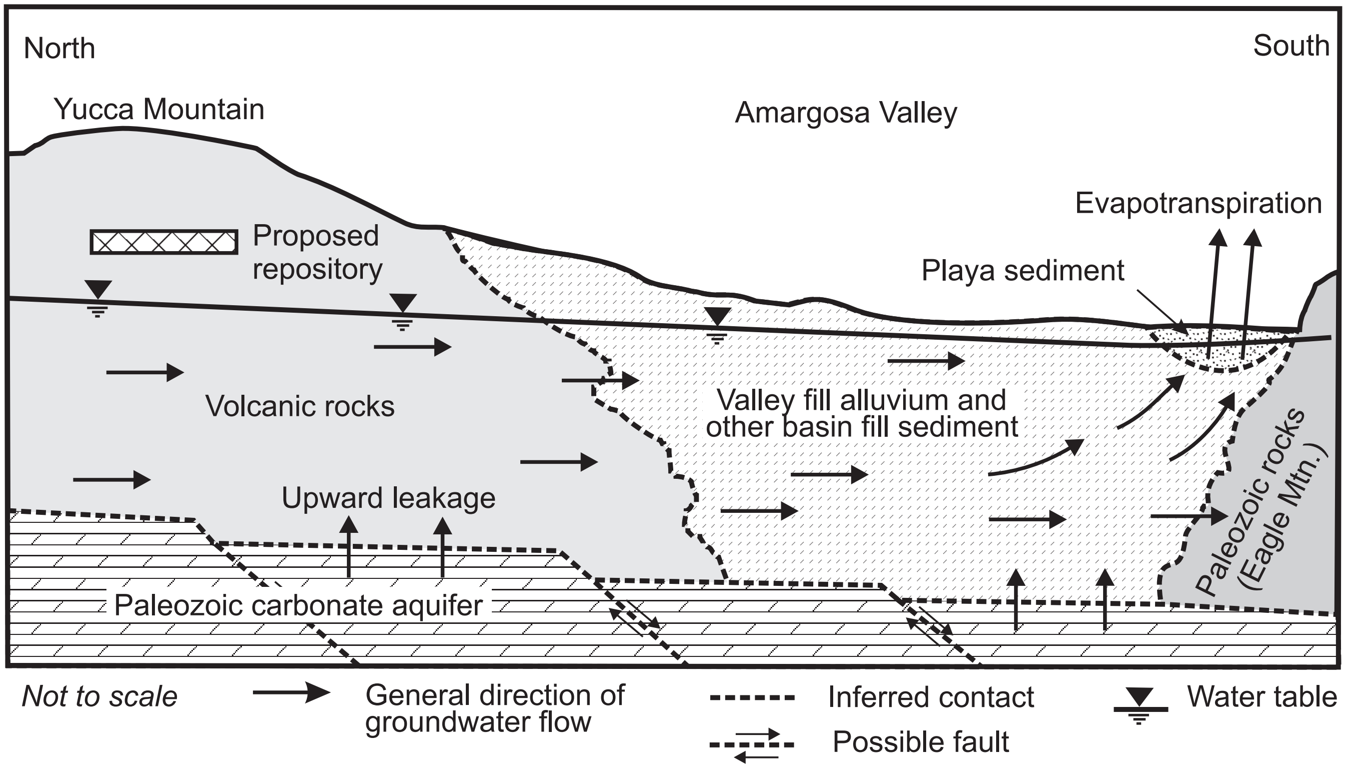
The primary hydrogeologic units that carry and influence the flow are the volcanic aquifer (consisting of the Upper Tram, Bullfrog, and Prow Pass formations), the volcanic aquitards (confining units) of the Calico Hills formation, the underlying and more permeable Paleozoic carbonate aquifer, and, to the south, the valley-fill alluvium. An idealized geohydrologic cross section from Yucca Mountain to Amargosa Valley is shown in Figure 1-3.

The SZ contributes as a natural barrier in two ways: (1) The SZ delays the transport of radionuclides to the accessible environment (increases the travel time); (2) The SZ reduces the concentration of radionuclides that entered from the UZ before they reach the accessible environment (through dilution). Characterization of the SZ has been influenced by

14. See July 30 letter from Jared L. Cohon to Lake Barrett (Cohon, 1998b).

15. The DOE initiated a License Application Design Study (LADS) in early 1999.

Figure 1-3. North-South Cross Section of SZ (after Czarnecki 1989)



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. 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.

SZ 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.

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[16] cannot be measured directly and require model predictions. The SZ transport model, which was to provide the expected dilution factor for the TSPA, was discarded in 1998. Because of the lack of data, SZ radionuclide transport was modeled for TSPA-VA by using a one-dimensional stream-tube model. The dilution factors for each stream tube were sampled randomly from the probability distribution functions elicited from experts (range of 1 to 100, expected value of 10) (Andrews 1998). Because of the short (modeled) travel times and small (assumed) dilution factors, the SZ contributed relatively little to repository performance as modeled in TSPA-VA.

16. 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.

B. The DOE's Scientific and Technical Work

Because of lack of funding, the anticipated pumping and tracer test facility, an analog to the C-well complex at a new location,[17] was postponed. Some additional hydraulic tests using reactive tracers were conducted in the Prow Pass interval at the C-well complex.

Additional hydraulic data were to have been obtained from the SD-6 and WT-24 boreholes. The work at SD-6 encountered drilling difficulties, so no information could be gathered below the water table. The drilling at the WT-24 well hole reached its planned depth, but it encountered a relatively tight part of the regional aquifer, so no pump testing could be conducted.

The regional 3-D groundwater-flow model of Death Valley Basin will be combined with the similar project being carried out at the Nevada Test Site by GeoTrans. This combination of resources and data will greatly enhance the possibility that a comprehensive model of the Yucca Mountain region will be forthcoming in a shorter time. A considerable amount of regional data downgradient of Yucca Mountain is expected from the proposed Nye County Early Warning Drilling Program (EWDP). There are almost no data about the alluvium and volcanics interface in this region.

C. The Board's Review Activities

Because of the much greater role that the SZ potentially plays in an evaluation of compliance with a dose-based standard, the Board extensively reviewed the DOE's work on the SZ during its January meeting in Amargosa Valley (NWTRB 1998b).

An overview of the SZ program and its objectives was presented by the DOE. The regional picture of the flow domain was summarized in three presentations on the regional 3-D groundwater-flow model of Death Valley Basin, the significance of hydrochemical domains in the SZ at Yucca Mountain, and a model for major ion chemistry of SZ waters along flow lines through Yucca Mountain. Although much has been learned in the last few years, the presentations illustrated the overall lack of hydrologic and geochemical data downgradient of Yucca Mountain. Alternative and additional testing and hypotheses of the SZ were presented by the State of Nevada and the Nye County EWDP.

Little transport data are available. The best data have been gathered at the C-well complex and were reviewed in the presentation on hydraulic and tracer testing at the C-well. These pumping tests and multiple tracer tests are at a single location in a single unit (the Bullfrog) and perhaps are not representative of the area between Yucca Mountain and Amargosa Valley. The potential "dilution" of the radionuclide concentrations as they move from Yucca Mountain to the accessible environment is a controversial subject. The subject was reviewed in the presentations on the preliminary 3-D finite-element groundwater-flow model of the SZ, on the status of the SZ flow-and-transport model, and on SZ flow-and-transport analyses in the TSPA.

The DOE had convened an expert panel to assess the status of the data and modeling of the SZ. Among the conclusions reached were (1) the data on the SZ are insufficient to elicit confidence in the model predictions; (2) the large hydraulic gradient north of Yucca Mountain is a common feature in this region and is consistent with the regional stratigraphy and hydrologic properties, and the probability that it is a concern for repository performance is exceedingly small; and (3) the large dispersion / dilution predicted by the transport model in the SZ is not based on any data and is scientifically unsupportable. The last conclusion caused the DOE and the M&O to change their transport computation for TSPA-VA. During the January Board meeting, two of the panel members were invited to present their views on the key issues and uncertainties for the SZ.

D. The Board's 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.

17. Three closely spaced wells were drilled near the proposed repository for conducting flow-and-transport tests in the SZ.

- Groundwater appears to move through Yucca Mountain to the accessible environment 20 to 30 km away in less than the 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 on the part of the SZ downgradient of Yucca Mountain. However, the wells may not provide sufficient data, and additional testing may be needed at other sites closer to Yucca Mountain.

V. Total System Performance Assessment

A. Overview

Total system performance assessment (TSPA) is the principal method of evaluating the ability of the proposed repository (engineered and natural components acting together) to contain and isolate waste. It is essentially a predictive-computational model or, more accurately, a collection of models of repository performance over time. Before completion of the TSPA for the VA (TSPA-VA) (USDOE YMPO 1998), major iterations of performance assessments were completed by DOE contractors for the Yucca Mountain site in 1991, 1993, and 1995. The initial TSPAs were conducted, although not always used, to provide guidance in gathering data and setting priorities in the scientific and engineering investigations being conducted by the Yucca Mountain Project. In addition to fulfilling that role, present and future TSPAs will be used to judge whether and to what extent the proposed repository is likely to meet the developing U.S. Environmental Protection Agency (EPA) and NRC safety standards.

B. The DOE's Scientific and Technical Work

In recent years, the primary focus of the DOE's effort in performance assessment has been the development of the TSPA-VA. As indicated previously, Congress directed the DOE to include in the VA a TSPA based on "... the design concept and on the scientific data and analysis available by September 30, 1998, describing the probable behavior of the repository in the Yucca Mountain geological setting in relation to the overall system performance standards" (U.S. Congress 1996).

A great deal of effort has been expended on the TSPA-VA. For example, in preparing for the TSPA-VA, the DOE conducted two lengthy series of workshops (mostly in 1997). The first series, called "abstraction and testing workshops," brought together field and laboratory scientists, modelers, and performance-assessment analysts from within the program to better define the process by which the highly complex models and data used to describe important phenomena in various areas could be simplified for inclusion in the TSPA-VA. The second series of workshops involved eliciting expert judgment, primarily from outside the Yucca Mountain Project, on the conceptual and parameter uncertainty associated with critical components and assumptions used in the TSPA.[18]

In 1998, the DOE devoted its efforts primarily to integrating the input from its own investigators and from external experts into the TSPA-VA. The results of the TSPA-VA consists of two main parts: (1) a base case emphasizing what the DOE considers the repository's expected or probable behavior and (2) a series of sensitivity tests aimed at estimating the effect on performance of different scenarios and alternative input parameters and design features.

An important part of the DOE's effort associated with the TSPA-VA has been an external peer review panel (TSPA Panel 1998). In 1998, the panel issued the third of its interim reports on the DOE's efforts. As in the previous reports (issued in 1997), the panel has shown itself to be both incisive and independent. In general, the panel pointed out the lack of site-specific data and the need to verify, as much as possible, the hypotheses, models, and abstractions used in the TSPA. The specific issues raised include the less-than-satisfactory characterization of SZ flow; the superficial treatment of coupled thermohydrologic, mechanical, and chemical interactions; the importance of crevice corrosion; and the need to provide experimental support for any credit taken for zircaloy cladding. A final panel report was released in February 1999. The DOE is to be commended for convening this panel.

C. The Board's Review Activities

In 1998, the Board's review activities that were related to TSPA centered on two meetings: an April 23-24 meeting of the Board's Panel on Performance Assessment in Albuquerque, New Mexico (NWTRB 1998c), and a presentation on TSPA at the June 24 summer Board meeting in Las Vegas, Nevada (NWTRB 1998e). At those meetings, the developing TSPA-VA was presented by the DOE and its contractors and discussed by Board members. Although the Board is continuing its review of the final version of the TSPA-VA, comments on these initial presentations were sent in a July 30, 1998, letter to Lake Barrett, Acting Director of the DOE's Office of Civilian Radioactive Waste Management (OCRWM) (Cohon 1998b). They are discussed below.

D. The Board's Conclusions

In general, the Board was pleased to see the refinements and improvements in the DOE's TSPA efforts. They were particularly evident in the efforts to make the TSPA more transparent—that is, understandable.

This latest analysis leaves the clear impression that the projected performance of the repository is very dependent on the corrosion resistance of the waste package and cladding. Any set of calculations, however, is only as valid as the underlying assumptions, models, and data. For example, the uncertainty analyses were highly dependent on the range of assigned parameter values. Important issues, such as cladding performance, did not appear important only because they were assigned a low uncertainty. Also not evident was whether the correlation between parameters, such as infiltration and seepage fraction, had been taken fully into account.

The Board recognizes the need to make judgments in any analysis. However, these judgments and their bases need to be stated explicitly and clearly. In 1997, the Board provided suggestions on how the DOE could meet this and other challenges. The suggestions appear in the Board report on its 1996 activities (NWTRB 1997a) and in a letter sent to April Gil (Cohon 1997) in response to the OCRWM's request for comments on proposed revisions to 10 CFR 960. In the report and the letter, the Board laid out suggestions on how to prepare a technically persuasive and robust performance assessment. The Board believes that the OCRWM's assessments should incorporate those ideas in its upcoming performance assessment for site recommendation.

18. The Board's 1997 summary report contains an extensive discussion of the DOE's use of expert judgment (NWTRB 1998a).