U.S. NUCLEAR WASTE TECHNICAL
REVIEW BOARD

Report to

The U.S. Congress

And

The Secretary of Energy

January to December 1999

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

April 2000

The Honorable Dennis Hastert
Speaker of the House
United States House of Representatives
Washington, D.C. 20515

The Honorable Strom Thurmond
President Pro Tempore
United States Senate
Washington, D.C. 20510

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

Dear Speaker Hastert, Senator Thurmond, and Secretary Richardson:

The Nuclear Waste Technical Review Board (Board) submits this *Report to The U.S. Congress and The Secretary of Energy* in accordance with provisions of the Nuclear Waste Policy Amendments Act of 1987, Public Law 100-203, which requires the Board to report its findings and recommendations to Congress and the Secretary of Energy no less than two times each year.

Congress created the Board to evaluate the technical and scientific validity of activities undertaken by the Secretary of Energy in characterizing a site at Yucca Mountain, Nevada, for its suitability as the location of a permanent repository for disposing of spent nuclear fuel and high-level radioactive waste. The Board also reviews the Department of Energy's (DOE) work related to the design of the repository and to the packaging and transport of spent fuel and high-level radioactive waste. In this report, the Board summarizes its major activities during calendar year 1999.

In 1999, the Board published its evaluation of the DOE's report, *Viability Assessment of a Repository at Yucca Mountain*, finding that Yucca Mountain continues to merit study as the candidate site for a permanent geologic repository and that work should proceed to support a decision on whether to recommend the site for repository development. The 2001 date for a decision is very ambitious, and focused study should continue on natural and engineered barriers.

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The Board believes that the performance assessment used by the DOE in the viability assessment can be the core analytical tool for estimating long-term repository behavior. However, performance assessment has limits and should be supplemented with other lines of evidence to make a robust safety case for a Yucca Mountain repository.

The Board has recommended evaluation of alternative repository designs, including lower-temperature designs, as a potential way to help reduce the significance of uncertainties related to predictions of repository performance. The Board looks forward to reviewing the design choices that the DOE will soon make.

Thank you for the opportunity to present the Board's views. We believe that this report provides useful technical and scientific information to the Secretary of Energy and Congress as they make important decisions on furthering the goal of safe management of spent fuel and high-level radioactive waste.

Sincerely,

Jared L. Cohon
Chairman

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Executive Summary

In 1987, the U. S. Nuclear Waste Technical Review Board (Board) was created as an independent federal agency by Congress in the Nuclear Waste Policy Amendments Act. The Board was charged with evaluating the technical and scientific validity of the U.S. Department of Energy's (DOE) efforts to develop a system for disposing of high-level radioactive waste and spent nuclear fuel. The Board is required to report its findings and recommendations to Congress and the Secretary of the DOE no less than twice a year.

This document describes Board activities undertaken during the 1999 calendar year. It presents the Board's views on the DOE's ongoing characterization of the Yucca Mountain site in Nevada as a potential location for a repository and summarizes other Board activities.

In 1999, the Board published its evaluation of the congressionally mandated report, *Viability Assessment of a Repository at Yucca Mountain* (*VA*) (DOE 1998a). The DOE report synthesized information collected over the last decade and a half and provided policy-makers with a "snapshot" in time of the following:

- preliminary waste package and repository designs
- estimates of repository performance
- additional research that DOE needs to conduct before deciding whether to recommend to the President that the site be developed as a repository
- total cost of constructing and operating a repository at Yucca Mountain.

The Board believes that Yucca Mountain continues to merit study as the candidate site for a permanent geologic repository and that work should proceed to support a decision on whether to recommend the site to the President for development. The 2001 date anticipated for this decision is very ambitious, and much work remains to be completed. At a minimum, progress on the work identified by the Board in its 1998 report (NWTRB 1998) and by the DOE in volume 4 of the *VA* (DOE 1998d) will be required to support a technically defensible decision. The Board supports continuing focused studies of both natural and engineered barriers at Yucca Mountain.

The Board believes that the performance assessment (PA) methodology used by the DOE in the *VA* (DOE 1998c) can be the core analytical tool for estimating long-term repository behavior. However, PA is limited, and the Board urges the DOE to supplement PA with other measures, such as defense-in-depth, to make a robust safety case for a Yucca Mountain repository.

The Board concluded that a credible technical basis does not exist for the repository design described in the *VA*. High temperatures in the *VA* design are likely to cause large uncertainties about how the site would behave both before and after repository closure. The Board recommended evaluation of alternative repository designs having lower temperatures of the waste package surface and tunnel walls. Although the Board has some concerns about the study that the DOE subsequently conducted, it is pleased that the DOE has moved toward implementing a lower-temperature design. However, many of the details of that design had not been finalized by the end of 1999. The Board looks forward to reviewing the design choices that the DOE will soon make.

Board Activities in 1999

During 1999, the U.S. Department of Energy (DOE) continued 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. The DOE also continued preparing designs for the packages in which the waste will be disposed of and the subsurface repository facilities. Along parallel tracks, the U.S. Nuclear Regulatory Commission (NRC) issued draft regulations evaluating a DOE license application for constructing a repository at Yucca Mountain (NRC 1999); the U.S. Environmental Protection Agency (EPA) published draft environmental standards that any such repository would have to satisfy (EPA 1999); and the DOE proposed draft guidelines for determining whether the Yucca Mountain site is suitable (DOE 1999).

Authorized by the 1982 Nuclear Waste Policy Act (NWPA) (U.S. Congress 1982) and the 1987 Nuclear Waste Policy Amendments Act (NWPAA) (U.S. Congress 1987), the DOE is scheduled to release the *Site Recommendation Consideration Report* (*SRCR*) in late 2000. The *SRCR* will be revised and will become the basis for a subsequent decision by the President on whether to seek congressional approval for developing a repository at Yucca Mountain. If approval ultimately is granted, the DOE will apply to the NRC for permission to begin constructing the repository.

The U.S. Nuclear Waste Technical Review Board (Board) is charged under the NWPAA with the responsibility of evaluating the technical and scientific validity of the work undertaken by the DOE to develop a system for disposing of spent fuel and high-level radioactive waste. In this report, the Board summarizes its activities in 1999. Because the DOE waste management program continues to evolve, some elements of it that are described in this report may have changed since the end of 1999.

I. The Board's Review of *Viability Assessment*

A. Overview

The DOE published *Viability Assessment of a Repository at Yucca Mountain* (*VA*) in December 1998 (DOE 1998a), and the Board offered its views on the *VA* in April 1999 (NWTRB 1999b). The purposes of the *VA* were to summarize the scientific information that has been collected at the site over the last 15 years, present a preliminary design for the repository and its waste packages, estimate how well such a repository would perform, identify the additional studies needed to evaluate the suitability of the site and prepare a license application, and estimate the total cost of constructing and operating a repository at the site.

The *VA* evaluates progress in site characterization at Yucca Mountain and presents the technical basis for deciding whether to continue studying the site. The *VA* is not, and is not intended to be, a determination of whether the Yucca Mountain site is suitable for development as a permanent geologic repository. Additional site studies, repository design work, and analyses of repository system performance will be completed before the DOE makes a suitability determination, currently planned for 2001. So far, neither the Board's review of the *VA* nor its other reviews of the program have identified features or processes that would automatically disqualify the site.

The *VA* is the most significant milestone thus far in the characterization and evaluation of the Yucca Mountain site. Many parts of the *VA* present cutting-edge scientific analyses in a comprehensible format. The Board commended the DOE for the successful completion of this assessment.

In assembling the *VA*, the DOE integrated large amounts of data and analyses, established a preliminary repository design, and set priorities for work to be completed before decisions are made about site recommendation and licensing. The process of integration had the salutary effect of focusing the objectives of the scientific investigations. In particular, the *VA* highlighted the close connections between the repository design and the priority list of key uncertainties about the natural system. For example, such site characteristics as the movement of water in liquid and vapor forms at temperatures above boiling and the effects of high temperatures on rock stability are important in a high-temperature repository design.

The *VA* concluded, "… Yucca Mountain remains a promising site for a geologic repository and … work should proceed to support a decision in 2001 on whether to recommend the site to the President for development as a repository." (DOE 1998b). The Board agrees that Yucca Mountain continues to merit study as the candidate site for a permanent geologic repository and that work should proceed to support a decision on whether to recommend the site to the President for development. The 2001 date anticipated for this decision is very ambitious, and much work remains to be completed. At a minimum, progress on the work identified by the Board in its 1998 report (NWTRB 1998) and by the DOE in volume 4 of the *VA* (DOE 1998d) will be required to support a technically defensible decision. The Board supports continuing focused studies of both natural and engineered barriers at Yucca Mountain to attain a defense-in-depth repository design and to increase confidence in predictions of repository performance. These views are discussed in greater detail below

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B. Need for Additional Scientific and Engineering Work

The DOE has spent many years studying the Yucca Mountain site and designing the engineered components of a repository system that is compatible with the site. These efforts have produced a large amount of information, but significant uncertainties remain about the ability of a Yucca Mountain repository to isolate radioactive waste safely. In part, this is a problem inherent in extrapolating repository performance for thousands of years from data acquired over a much shorter period (years to decades). Uncertainties also are associated with specific characteristics of the Yucca Mountain site, especially the nature of water movement through the fractured unsaturated rocks of the mountain and the possible entry of water into repository tunnels and its contact with waste packages. Many of these uncertainties likely would be exacerbated by a high-temperature repository design, which may reduce tunnel stability, increase waste package corrosion, and perturb geochemical reactions and water movement in ways that are difficult to predict.

The Board believes that the scientific and engineering work completed to date should be supplemented to improve the technical foundation for evaluating the suitability of the site or preparing a license application. In volume 4 of the *VA* (DOE 1998d), the DOE identified and set priorities for a suite of additional studies for producing information that would be needed for repository licensing, if the site is determined suitable for development as a repository. The planned studies include data collection, analysis, and engineering design, as appropriate, for the three major barriers: unsaturated zone, engineered system, and saturated zone.

Among the most important activities are ongoing and proposed geologic, geochemical, and hydrologic studies of the unsaturated zone, including those planned for the east-west cross drift. The studies are aimed at understanding the magnitude and distribution of seepage into the repository under conditions similar to those of today and under conditions like those that existed in the past, when the climate was wetter. The studies include systematic analysis of the rock samples being collected, especially for chlorine-36 and other indicator isotopes;

flow and seepage tests at different locations along the drift; moisture-monitoring activities; tests in the lower lithophysal zones that would host the majority of waste packages; and studies of the Solitario Canyon fault, the active fault bounding the repository on the west.

Predicting the performance of the waste packages, which play a crucial role in the current Yucca Mountain repository design, is a critical area that needs more study. Candidate waste package materials rely on the presence of a thin passive layer to protect the underlying metal from the oxidizing environment that would be present in a Yucca Mountain repository. Improving the basic understanding of long-term passivity is essential because, at present, there seem to be no documented natural or man-made analogs that can be used to demonstrate whether this mode of protection would last over thousands of years. Research also should be continued on the susceptibility of the passive layer to known modes of corrosion, especially potential catastrophic-failure modes, such as stress-corrosion cracking.

The studies identified by the DOE in volume 4 of the *VA* (DOE 1998d) appear to be appropriate in the sense that they are technically feasible and are likely to produce useful information that will improve the understanding of long-term repository performance. Of course, there is no guarantee that completion of these studies will lead to successful development of a repository at the site. The studies could show the site to be unsuitable, or they could raise new questions about potential repository performance.

The Board is concerned that some of the planned studies identified in volume 4 of the *VA* may be deferred because funds are not available to carry them out in a timely manner. Deferring scientific and engineering studies will delay the assembly of a more credible technical basis to support the site suitability determination and, if the site is found suitable, a subsequent license application.

C. Need for Evaluation of Alternative Repository Designs

In the Board's view, a credible technical basis does not exist for the repository design described in the *VA*. High temperatures in the *VA* repository design would cause large uncertainties about how the site would behave both before and after repository closure. The Board therefore recommended that the DOE evaluate alternative repository designs having lower temperatures of the waste package surface and the tunnel walls. Such designs have the potential to reduce uncertainty, simplify the analytical bases and models required for site recommendation, and make licensing easier. Combined with improved waste package shielding, such designs also could simplify preclosure performance confirmation (1) by enhancing access to the tunnels, thus reducing or eliminating the need for separate performance-confirmation drifts and (2) by permitting direct access to performance-confirmation instrumentation near the waste packages.

D. Need for Long-Term Scientific Studies

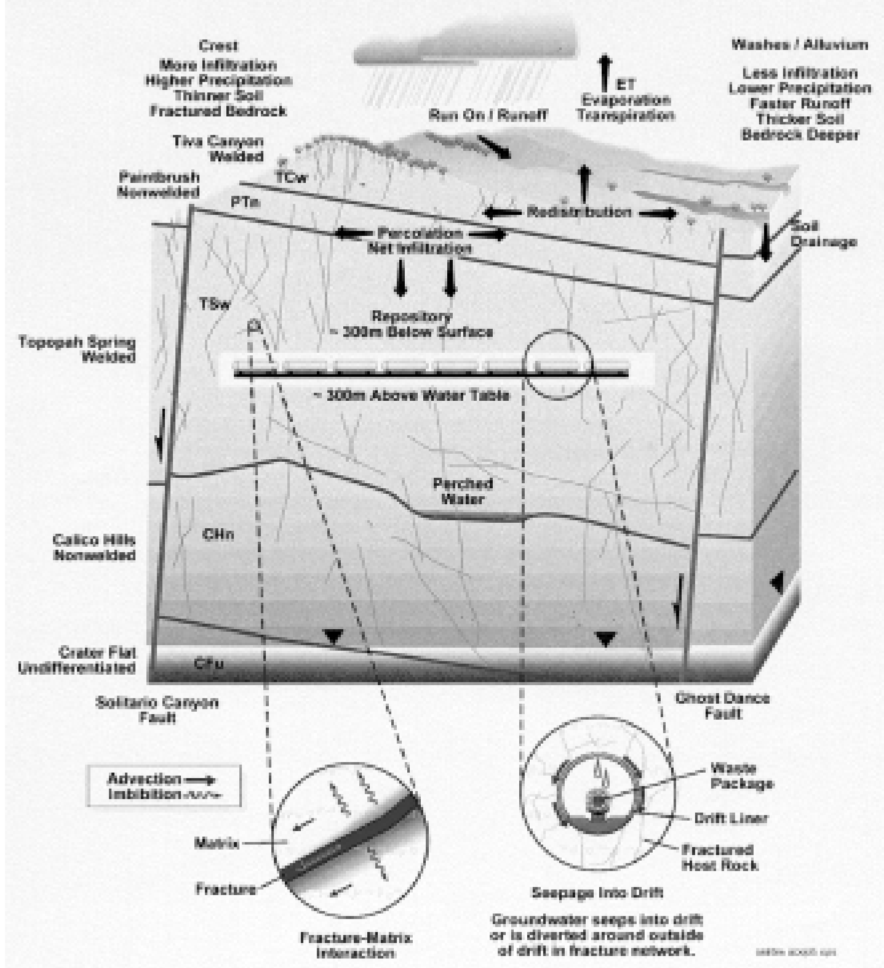
If Yucca Mountain is found suitable and construction of a repository is authorized, the Board believes that a long-term science program, including monitoring, will be needed to improve understanding and reduce uncertainties about the performance of engineered barriers and the interactions between the repository and natural processes. An important goal of these studies should be identifying currently unknown long-term failure modes or unexpected evolution of natural processes that could adversely affect the performance of the major barriers of the repository. Thus, the studies may be more extensive than the performance-confirmation activities now anticipated for a repository. For example, long-term scientific studies need to be carried out to improve further the basic understanding of the processes that could affect the waste package's passive layer. Long-term studies of the natural barriers also will be needed, primarily to verify projections of water movement within the unsaturated and saturated zones near the repository.

Whether the long-term scientific studies are a decade-long program or a much longer one will depend in part on how the repository design evolves. There is no doubt, however, that a research program of some sort will be needed to increase confidence in estimates of long-term repository performance.

II. The Board's Review of Investigations in the Unsaturated Zone

A. Overview

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



The unsaturated zone (UZ) at Yucca Mountain is a critical geologic component of the proposed repository system. Other countries around the world rely on a waste isolation strategy in which high-level nuclear waste is disposed of in rock (typically granite, clay, or salt) in the saturated zone—that is, below the water table. The U.S. waste isolation strategy, however, calls for placing the waste in volcanic tuff in the UZ—that is, above the water table. This strategy presents both opportunities (little water in the surrounding rock to corrode waste packages and transport waste) and challenges (characterizing UZ flow and transport). At Yucca Mountain, the repository will be approximately 300 meters below the earth's surface and some 300 meters above the water table. The UZ will be the medium through which precipitation will have to infiltrate into the overlying soil and rock, percolate down to the repository horizon, and seep into the waste emplacement drifts. If the waste packages corrode and water reaches and dissolves nuclear waste, the radionuclide-bearing water will have to move through the unsaturated rock below the repository to reach the saturated zone, where it may be transported to the accessible environment.

The UZ is made up of alternating layers of welded and nonwelded mid-Miocene (10 to 13 million years old) volcanic tuff. (See Figure 1-1.) The welded tuffs are harder and more fractured than the nonwelded tuffs. The uppermost part of the UZ is the Tiva Canyon welded unit (). The TCw is underlain by the Paintbrush nonwelded unit (PTn). Beneath the PTn is the Topopah Spring welded tuff (TSw), the rock layer in which the repository will be placed. Beneath the TSw is the Calico Hills nonwelded unit (CHn) and the Crater Flat undifferentiated unit (CFu). The repository "block," about 5 km long and 1.5 km wide, is bounded on the east by the Ghost Dance fault and on the west by the Solitario Canyon fault.

B. The DOE's Scientific and Technical Work

In 1999, the DOE focused its scientific research on several topics, including seepage, retardation, and thermal effects. This work was carried out in the east-west cross drift, which is the main component of the "enhanced characterization of the repository block" (ECRB); the exploratory studies facility (ESF); and the Busted Butte facility. These investigations are described below.

1. Tests in the East-West Cross Drift

The east-west cross drift, commonly called the "ECRB" or the "cross drift," is a 2,500-meter-long tunnel extending from the ESF to the Solitario Canyon fault. It was completed in October 1998 and crosses the repository block just above its proposed horizon. Of particular importance is its penetration of the lower lithophysal unit of the TSw. (Lithophysal cavities are hollow bubble-like structures that vary in size. They are formed by gases in cooling volcanic rocks.) This unit is now planned to be the host rock for more than 75 percent of the nuclear waste. This unit essentially was not exposed in the ESF, which has served primarily as a means of investigating the middle nonlithophysal unit of the TSw.

Systematic mapping carried out thus far generally has confirmed structural predictions made before the excavation of the cross drift, although some unanticipated minor faults were discovered that were not revealed at the surface. Preliminary testing for chlorine-36 has revealed a high level of bomb-pulse chlorine-36 at one of these faults. The presence of this isotope, generated by aboveground nuclear testing in the 1950's, has been taken as an indicator of rapid groundwater percolation through some faults and fractures. Hydrologic testing has found matric or capillary water potential (a measure of suction in empty or partially empty rock pores) to be lower than anticipated, indicating that the rocks may be wetter than originally thought. This observation is being tested using various measuring techniques.

Fracture mapping shows that the lower lithophysal unit has significantly fewer fractures that are a meter or more in length than the middle nonlithophysal unit mapped in the ESF does. Additional mapping is under way to determine whether the difference in fracture density also is true for shorter fractures. Of particular significance is the observation that water used in the construction of the cross drift penetrated to a depth of only 3 m in the upper lithophysal unit in comparison to 30 m in the middle nonlithophysal unit. The upper lithophysal unit lies just above the middle nonlithophysal unit, and the lower lithophysal unit lies just below. This apparent difference in permeability between lithophysal and nonlithophysal units is being investigated to determine both its veracity and its significance. Large differences could limit the usefulness of insights gained from the extensive testing of water movement in the middle nonlithophysal unit in the ESF.

The cross drift is providing a unique opportunity to observe the movement of water in the rocks in which the majority of nuclear waste may be placed. In June 1999, approximately 1 km of the cross drift was closed off by bulkheads so that moisture changes and possible seepage into an underground drift, unaffected by the drying effects of ventilation, could be observed. This test will last for about 1 year. Remote testing and periodic inspection visits to the closed-off drift will provide useful information. A similar small-scale test in the ESF is described below.

Outside of the closed-off section of the cross drift, initial work also is under way for testing air permeability and seepage in the rocks exposed in the cross drift. Air permeability is used as a surrogate for water permeability in rock fractures. A short excavation, or niche, in the lower lithophysal unit also will be used to improve understanding of seepage. Water will be injected just above the niche, and observations will be made of how long the water takes to travel to the niche and how much water penetrates into the niche. A somewhat similar test will be conducted at the point where the cross drift crosses over the ESF, some 30 m below. Instrumented boreholes extending downward from the cross drift and upward from the ESF will track the movement of water.

2. Tests in the ESF

Some studies in the 8-km-long ESF have been phased out, but others continue, mostly related to seepage and thermal testing. A long-duration test of near-surface infiltration and seepage into an alcove (a side excavation in a drift somewhat larger than a niche) in the TCw entered its second phase. Water is being applied at the surface, 20 m or more above the alcove, resulting in artificially high rates of infiltration into the mountain. Approximately 10 percent of the applied water has been seeping into the alcove. Models indicate that 50 percent of the fractures contain flowing water and that matrix diffusion is effective in retarding tracers included in the water.

A possibly more relevant seepage test was carried out in an alcove deeper in the mountain in the TSw. There, seepage was measured using water injected just above the alcove. Those seepage measurements are being used to help calibrate the seepage model that will be used in an upcoming total system performance assessment (TSPA), discussed later in this chapter. Based on this calibrated model, estimates are being made of the seepage threshold—that is, the rate of percolation needed before seepage into the drifts will begin. A very preliminary estimate was that this threshold is 1,000 mm/yr for seepage into a smooth (nondegraded) drift in the middle nonlithophysal unit (Bovardsson 1999). The estimate is being revised downward significantly. Two 70-meter sections of an alcove in the TSw near the Ghost Dance fault were closed off in an attempt to capture any increased infiltration and percolation that are due to increased precipitation from the 1998 El Nino event. No seepage was measured or observed.

Given the significance of the presence of bomb-pulse chlorine-36 discussed above, the DOE began a validation study of previous results at two locations (the Sundance fault and the Drillhole Wash fault) where bomb-pulse chlorine-36 had been discovered in the ESF. Numerous new samples were collected and are being tested for chlorine-36 and other possible bomb-pulse indicators, such as tritium and technetium-99. Similarly, total chloride measurements were made and have been analyzed at various locations in the ESF and the cross drift. The presence of chloride is taken as a measure of the extent of evapotranspiration near the surface and as an inverse indicator of the amount of water able to percolate downward into the mountain. On the basis of these measurements, percolation flux is estimated to be lower and more uniformly distributed than estimates derived from surface-based infiltration studies and models.

The drift-scale thermal studies being carried out in a large alcove off the ESF are half way through the 4-year heat-up stage, and the rock near the drift has reached temperatures above the boiling point of water. The heat-up will be followed by 4 years of cool-down. This heavily instrumented study of the effects of heat on rock and movement of moisture in the vicinity of a simulated waste-emplacement drift provides an opportunity to make full-scale observations of coupled processes and tests of model predictions. Thermal, hydrologic, mechanical, and chemical coupled processes are being investigated. Among the conclusions reached thus far is that temperature is fairly well predicted because heat conduction, not hydrologically controlled heat convection, is the primary means of heat transfer. The movement of moisture is more difficult to predict and harder to observe because of the need to rely on indirect geophysical methods whose resolution may be less than desired. Within the resolution provided, heated water appears to be moving down around the sides of the drift and not accumulating above the drift, although it may be accumulating below the drift. Very important to note is that this test is being conducted in the middle nonlithophysal unit of the TSw. A test in the lower lithophysal unit exposed in the cross drift is being considered.

A 2-year cooperative study of fluid inclusions exposed in the ESF and the cross drift began in the spring of 1999. The study grew out of contentions by State of Nevada researchers that fluid inclusions provided evidence of ongoing hydrothermal upwelling in Yucca Mountain. The evidence for such upwelling was reviewed by the Board in 1997 and 1998 and was reported on in a Board letter (Cohon 1998) to the DOE and in a Board report (NWTRB 1999a). Although the Board found that no credible case had been made for the hypothesis of ongoing hydrothermal upwelling, it pointed out the equivocal nature of one class of evidence, fluid inclusions, and recommended that the ages of fluid inclusions indicating the presence of fluids at elevated temperatures be determined. The Board also recommended that such a study be carried out in a joint program involving federal and State of Nevada scientists that could help eliminate past disagreements over sample collection and handling.

The DOE has funded such a study, and it is being conducted by scientists at the University of Nevada at Las Vegas in conjunction with scientists from the U.S. Geological Survey and the State of Nevada. In the ESF and the cross drift, 150 samples have been collected, and detailed petrographic analysis of the sequence of secondary mineralization is under way. Many fluid inclusions have been found, and their distribution and temperatures of formation will be determined, along with estimates of when they were formed. University of Nevada scientists have confirmed that watery fluids with elevated temperatures (loosely defined as somewhere between 25º and 100º C) moved through the rock at some unknown time in the geologic past. However, they have not determined yet the temperature of this fluid, the time the fluid moved through the rock, or whether the fluid descended from the surface or rose from depth.

3. Investigations at Busted Butte

Work continues at the Busted Butte facility, some 6 km southwest of the proposed repository. This shallow 70-meter-long drift was constructed to examine a near-surface extension of the CHn unit underlying the repository. The significance of the CHn is in its ability to retard the transport of radionuclides released from the repository. At the inception of the Yucca Mountain program, much emphasis was placed on the highly part (CHnz) of this nonwelded tuff because migrating radionuclides could be sorbed onto the surface of the zeolites and their travel time to the environment could be delayed significantly. Subsequent evaluations of the CHnz revealed extensive fracturing that could allow the quick passage of fluids and not provide an opportunity for radionuclide sorption and retardation. The Busted Butte facility concentrates on the vitric, less zeolitized part (CHnv) of the CHn. This unit has many fewer fractures and may retard the radionuclide movement because of the very slow movement of water through the unfractured rock matrix.

Phase 1 tests in a wall of the facility have been completed, and Phase 2 tests in an isolated 19-meter-long test alcove are under way. Fluids with tracers are injected and collected, and their movement is monitored by moisture pads and geophysical techniques. After each phase of the experiment, the rock wall in which the fluids were injected and collected is mined back to detect tracer migration rates and pathways.

Analysis of the Phase 1 tests indicates long travel times in the CHn and migration of water into the rock matrix where sorption and retardation can take place. The DOE believes that the Phase 2 tests, when analyzed, may have a strong effect on dose estimates.

C. The Board's Review Activities

Results of ongoing tests in the UZ were discussed at all Board meetings in 1999. Board members and Board staff members attended smaller meetings devoted to progress in areas such as thermal testing and fluid inclusions. The UZ also was discussed at DOE-NRC technical exchanges. The Board's review of critical analysis / modeling reports (see the discussion of TSPA later on in this chapter) on UZ topics, such as seepage calibration model and seepage testing data, has started.

D. The Board's Conclusions and Recommendations

The Board places great emphasis on the need to determine the thermal, hydrologic, mechanical, and geochemical properties of the proposed rock units in which the nuclear waste will be placed. The importance of conducting tests in the lower lithophysal unit of the TSw (the proposed host rock for more than 75 percent of the waste) cannot be overemphasized. The DOE therefore is commended for its decision to excavate and conduct tests within the cross drift, where this unit is exposed. Similarly, closing off 1,000 m of this drift to examine the movement of moisture in the rock near the drift, without the effects of ventilation, is very important. We urge the DOE to continue along this path and ensure the completion of studies related to seepage and to thermal tests within the cross drift.

Because drift seepage is such an important component of the natural system and has proven to be a significant contributor to dose estimates, the Board urges the DOE to incorporate realistic drift conditions in its models, taking into account both possible drift degradation and the rocks in which the drifts will be placed. Seepage tests in the cross drift will help in this effort.

Finally, the Board recognizes the potential benefits obtained from the Busted Butte tests. The CHn could emerge as an important natural barrier and play a key role in any defense-in-depth strategy. One critical aspect of this study not fully addressed in past meetings needs to be analyzed: the applicability of test results at Busted Butte to the rocks directly beneath the repository. At this time, the extent to which available stratigraphic data allow a meaningful extrapolation from Busted Butte to the repository footprint is unclear to the Board.

III. The Board's Review of Repository and Waste Package Designs

A. Overview

For the design of the repository, the engineering barrier system, and the waste package and for activities supporting design, 1999 was a momentous year. Studies of design alternatives, started during the later phases of work on the *VA*, were brought to completion, resulting in the recommendation and then adoption of a design having some key features that are significantly different from those of the *VA* design. In particular, the current design uses modest amounts of ventilation for periods of 50 years or more, compared with essentially no ventilation in the *VA* design. The current design uses a waste package with Alloy 22 on the outside of the waste package rather than on the inside as in the *VA* design. The current design also uses a drip shield, a feature that was not in the *VA* design.

Substantial efforts were made in 1999 in evaluating waste package performance. The potential for stress-corrosion cracking of Alloy 22 was confirmed by laboratory results, leading to an increased focus on reducing or eliminating residual tensile stresses in the heat-affected zone surrounding the waste packages' final closure welds. Work on documenting early failures in commercial welded metal containers continued in an effort to increase understanding of the potential for early failures of waste packages and drip shields. At the pilot scale, progress was made in understanding the effects of backfill with and without a drip shield.

B. The DOE's Scientific and Technical Work

The DOE continues to develop its designs for the repository, the waste package, and the engineered barrier system (EBS). These efforts are described in turn.

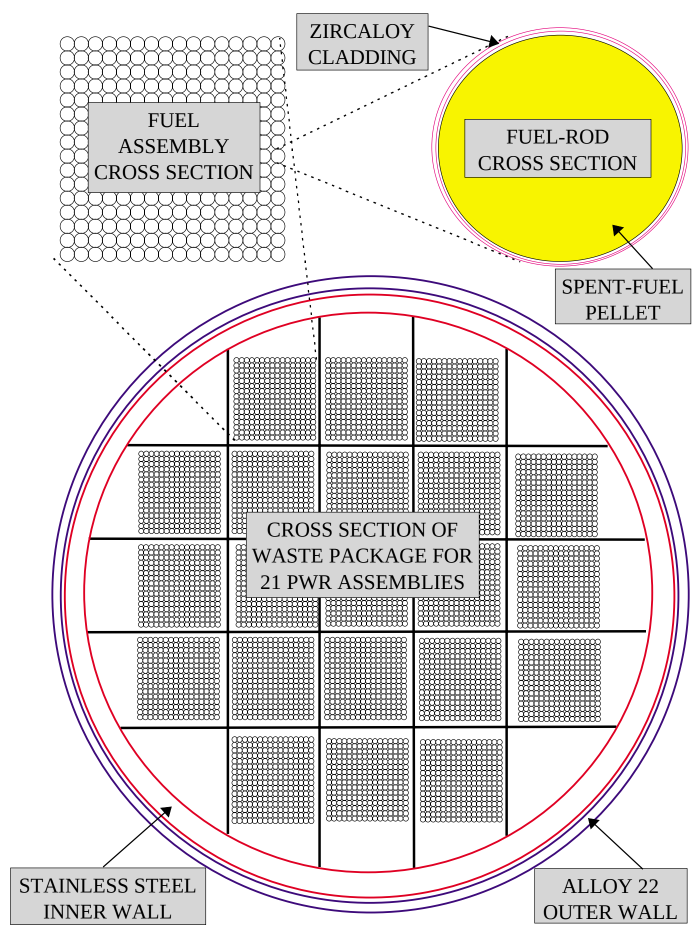
1. License Application Design Selection Study

In late 1998, following completion of the *VA*, the DOE's management and operating contractor (M&O), initiated the License Application Design Selection (LADS) study. The purpose of the study was to select the repository and waste package designs that would form the bases for the site recommendation decision and for the subsequent application to the NRC for a license to construct the repository. In 1999, the LADS study continued, at an expanded scale of effort, evaluations of design alternatives that took place during preparation of the *VA*. After additional analyses, the DOE announced its acceptance, with conditions, of the recommended LADS study design concept, known as Enhanced Design Alternative II (EDA-II), in a September 10, 1999, letter to the Board (Barrett 1999).

The following paragraphs discuss the LADS study, the DOE's acceptance of the LADS study recommendations, and the Board's findings, conclusions, and recommendations about the LADS study process and outcome.

a. Waste Package Design

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



Because of the many different wastes requiring geologic disposal, different types of waste packages will be used. In the current planning for a repository that would accommodate 70,000 metric tons of waste, the DOE indicates that the most common waste package would contain 21 pressurized- water reactor (PWR) assemblies. (See Figure 1-2.) Because the outer walls of all waste packages would use the same materials as the 21-PWR waste package, because nearly all other waste packages would be the same size or smaller than the 21-PWR waste package, and because the few that exceed the 21-PWR waste package in size are only slightly larger, using the 21-PWR waste package as a surrogate for all waste packages is convenient. The 21-PWR waste package conceptual design is a dual-wall cylinder approximately 1.6 m in diameter by 5 m long. The outer wall is Alloy 22 and is 20 mm thick. The inner wall is nuclear-grade 316 stainless steel and is 50 mm thick. The waste package includes 50-mm-thick Alloy 22 extensions at each end for handling.

Although the exterior dimensions are almost the same, there are major differences between the LADS waste package design and the *VA* waste package design. The *VA* waste package design also is a dual-wall cylinder, but its outer wall is 100-mm-thick carbon steel and its inner wall is 20-mm-thick Alloy 22. (Eliminating the carbon steel eliminates most concerns about uncertainties caused by “oxide-wedging.” In the *VA* design, when oxidation of the carbon steel penetrates the outer wall of the waste package, further oxidation of the steel along the crevice between the inner and outer walls conceivably could result in wedging forces large enough to cause failure of the inner wall.)

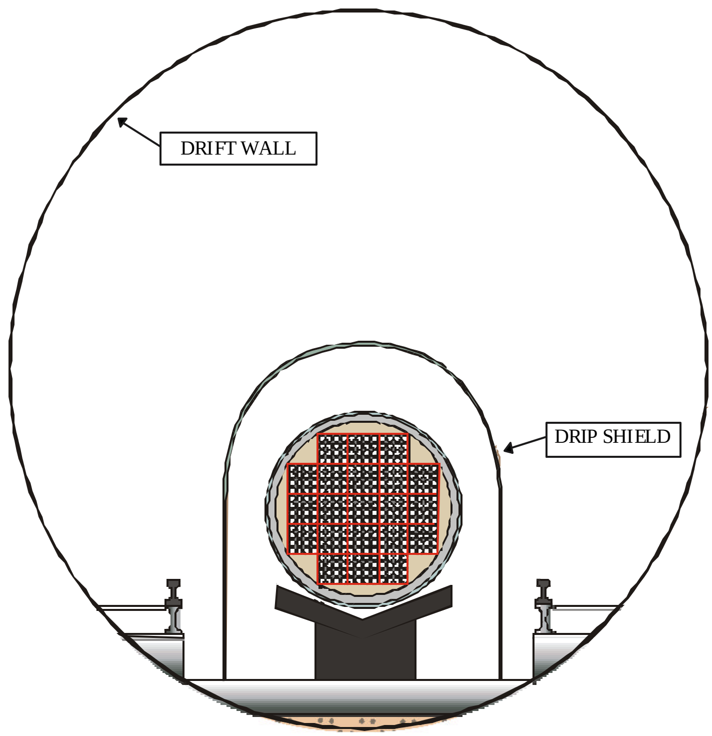
The proposed method for constructing the *VA* waste package was to shrink-fit the inner and outer walls to obtain a tight fit. To prevent the tensile stresses on the outer wall that shrinkfitting could cause, the LADS study design would not use shrinkfitting; thus, there would be a very small gap between the waste package’s inner and outer walls.

For these reasons, and others, according to the LADS report, the LADS study waste package design would have a longer life than the *VA* waste package design (CRWMS 1999), even though both waste package layers were credited with improving waste package performance in the *VA*, but only the Alloy 22 layer was credited in the LADS study.

b. EBS Design

Although the term "engineered barrier system" normally refers to all engineered (as opposed to natural) components of the repository and thus includes the waste package, we use it here to refer to engineered components outside the waste package. The LADS study EBS design includes a 15-mm-thick drip shield of Grade 7 titanium. (See Figure 1-3.) The function of the drip shield, which is a curved sheet of material over the waste package, is to prevent water from dripping onto waste packages. The drip shield would be covered by partially filling the drift with a layer of granular backfill that is thick enough to protect the drip shield from rock falls. The drip shields and the backfill would not be added until near the time of repository closure. Although the *VA* EBS design could have drip shields and backfill, it does not have them. According to the DOE, incorporating drip shields and backfill in the LADS study design offers the potential for significant improvement in both performance and defense-in-depth.

Figure 1–3. Cross Section of EBS and Waste Package



c. Repository Design

The LADS repository design features areal mass loading of approximately 60 metric tons per acre, spacing between drifts of 81 m, and ventilation throughout the preclosure period at the nominal rate of 10-15 cubic meters (m^3) of air per second per emplacement drift. To enhance flexibility, the DOE placed three conditions on the LADS study design for the time the repository would or could be closed:

- The design will permit the repository to be closed at any time from 50 years to approximately 125 years after the start of waste emplacement.
- The design will permit the repository to be kept open for approximately 125 years from initiation of waste emplacement with only routine maintenance.
- The design will not preclude keeping the repository open, with appropriate maintenance and monitoring, for 300 years after initiation of waste emplacement.

The LADS study repository design depends on the assumptions that waste packages can be placed as close as 100 mm apart and that blending will be used to ensure that the peak waste package heat output at time of emplacement would be no greater than 11.8 kilowatts (kW). Ground support for the LADS repository design consists of carbon-steel ribs or rock bolts.

The LADS study repository design represents a major departure from the *VA* repository design in many respects. The most significant departure is the use of ventilation in the LADS study design, as opposed to the essentially nonexistent ventilation in the *VA* design. Ventilating each emplacement drift with 10-15 m^3 of air per second would keep drift-wall temperatures below 70°C during the preclosure period and would decrease postclosure drift-wall temperatures substantially in comparison to the *VA* design. For example, ventilating at 10-15 m^3/sec/drift for 125 years following emplacement initiation would result in drift-wall temperatures no higher than 96ºC for the entire postclosure period. (The approximate boiling point of pure water at the altitude of the proposed Yucca Mountain repository is 96ºC. The range of boiling temperatures for water at Yucca Mountain will be above the boiling point of pure water because of dissolved salts and capillary forces.) In contrast, in the *VA* repository design, *peak* preclosure drift-wall temperatures could exceed 150ºC within a year after emplacement, and average drift-wall temperatures could stay above the boiling point of water for hundreds of thousands of years.

2. Waste Package Performance

a. Stress-Corrosion Cracking

Stress-corrosion cracking (SCC) is a form of environmentally induced cracking where local moderate-to-high tensile stresses and localized corrosion combine to cause the rapid propagation of a crack. SCC testing of Alloy 22 and titanium under severe conditions (near-boiling temperatures, high salt concentrations, very acidic or very basic conditions) shows that both materials undergo SCC. SCC is less of an issue for titanium, which would be used only in the drip shield, than it is for Alloy 22. Properly manufactured, inspected, and handled, the drip shield is unlikely to have areas with moderate-to-high residual tensile stresses. However, unless the heat-affected zone (HAZ) in the vicinity of the final closure weld of the Alloy 22 outer wall of the waste package is specially treated, this zone is likely to contain moderate-to-high residual tensile stresses.

Three parallel efforts are under way within the program to increase the understanding of SCC and the possibility of preventing it:

> *Development of more experimental data on SCC.* The data will be taken in different environmental conditions, including less severe conditions, lower temperatures, and different stress intensities. Commercial and government laboratories are involved. One goal will be to determine if there is a threshold stress-intensity level below which no crack propagation occurs and how this level might vary with environmental conditions.

> *Heat treating of the Alloy 22 HAZ (by inductive heating).* If successful, this process will virtually eliminate residual tensile stresses in the HAZ and thus essentially eliminate the possibility of SCC. (To implement this approach, the DOE redesigned the final closure weld to locate it at the very end of the waste package.)

> *Laser peening of the Alloy 22 HAZ.* If successful, this process will place the outer millimeter or so of the HAZ in compressive stress, eliminating SCC for as long as the thin layer in compressive stress remains. (According to the current waste package degradation model, however, if the highest general corrosion rate in the model is used, this layer could be penetrated by general corrosion in a few waste packages in less than 10,000 years.)

b. Early Failures of EBS Components

Early failures (sometimes called "premature failures" or "juvenile failures") of EBS components are penetrations (e.g., cracks, holes) that, because of manufacturing or handling errors, occur earlier than they otherwise would. Examples of root causes of early failures are a faulty weld, improper heat treatment, gouging of a waste package while it is being moved, dropping of a loaded waste package (which might damage not only the package but also the waste form in it), and use of out-of-specification materials. Sensitivity analyses performed for TSPA-VA indicate that early failures would be a very important contributor to the peak dose over the first 10,000 years of a repository's life. Specifically, the TSPA-VA models showed that the occurrence of an early failure (a failure 1,000 years after repository closure) of a waste package located in a tunnel with water dripping overhead would cause waste radionuclides to arrive at a point 20 km from the repository approximately 5,000 years after repository closure, which is roughly 2,500 years earlier than if no early failure had occurred. Early failures do not appear to have a significant effect on long-term (longer than 10,000 years after repository closure) peak doses, according to TSPA-VA analyses.

The current design of the EBS is very different from the design of the VA. Two major changes are that the Alloy 22 wall is now on the outside of the waste package and that there is now a drip shield (titanium) over the waste package. Together, these two changes should substantially increase EBS life in comparison to the VA design. Assuming that the current waste package design is no more susceptible to early failure than the former design, adding the drip shield should decrease the probability of early EBS failure, in addition to increasing EBS life.

Predicting how many early EBS failures would occur and when they would occur is very difficult. The occurrence of early failures is a function of detailed EBS design, specifications, manufacturing procedures, handling procedures, inspection procedures, and repair and reinspection procedures, none of which is likely to exist for at least several years. Early failures also are a function of how well procedures are followed (human error). In the meantime, the project seems to be making the implicit assumption that manufacturing and inspection procedures for the waste package will be at least as good as commercial practices for welded metal containers (e.g., pressure vessels) and that therefore early-failure data for such containers can be used to obtain a conservative upper bound on early failures of waste packages related to manufacturing and inspection.

Applying these data to estimate or bound early failures of the waste package will not necessarily be straightforward, however, for two reasons: (1) the high radioactivity of the contained waste requires that the waste package's final closure weld and its inspection be done remotely, but most of the data are from manufacturing and inspection operations that were not done remotely; and (2) the database of early failures for conventional welded metal containers generally consists of failures that have occurred within the first few decades after the containers were placed in service, whereas early failures of waste packages containing high-level waste will occur over a much longer period.

c. The Atlas Facility

Recognizing the potential benefits to performance, defense-in-depth, and physical protection of the waste package that the EBS components outside the waste package might provide, the DOE launched a pilot-scale EBS research program in mid-1998 at a DOE facility in North Las Vegas. The first test at the facility was a quarter-scale demonstration of a Richard's barrier. (A Richard's barrier is a capillary barrier created by covering an object with a layer of coarse rock [e.g., gravel] covered by a layer of fine rock [e.g., sand]. Capillary forces cause water that drips onto the fine layer to remain in the fine layer, thus routing the water around the object and keeping it dry.) The test successfully demonstrated the Richard's barrier concept at ambient temperature. However, additional Richard's barrier tests were not pursued, because the design selected by the DOE does not contain a Richard's barrier.

More recent pilot-scale EBS testing at the North Las Vegas facility directly supports the LADS study design. Quarter-scale equipment similar to that of the Richard's barrier test is used, but the equipment can be operated at elevated temperatures and incorporates a drip shield, as well as backfill covering the drip shield. Testing is being done by dripping water at controlled rates onto the backfill and observing and measuring where the water flows. Test results will help establish whether condensation on the inside surface of the drip shield is likely, the degree to which the backfill may protect the drip shield from dripping water, and the amount of water in the invert that is drawn back toward the waste package.

C. The Board's Review Activities

Design of the repository and the EBS was the principal topic at two of the Board's public meetings in 1999: the January 25 meeting in Las Vegas of the Board's Repository Panel and the June 29-30 meeting of the full Board in Beatty, Nevada. In addition, one or two Board members or one or two staff members, or both, attended, as observers, several design-related meetings between DOE and NRC personnel and their contractors, as well as several meetings among DOE and M&O personnel on design-related topics, such as criticality, heat-transfer calculations, ventilation, and drift support.

D. The Board's Conclusions and Recommendations

1. The LADS Study Process

The LADS study was a major focused effort that grew out of design-alternative studies performed in support of the *VA*. Because the Board has considered repository design a key issue for a long time, the Board is pleased that the LADS study was undertaken. The study produced a much better understanding of the relative importance of the many factors involved in a repository design.

The Board, however, has concerns about a few of the key aspects of the process that the DOE used to carry out the study. The Board recognizes the need to make value judgments in any analysis. The Board also realizes that such judgments bring to bear technical, policy, cost, or resource considerations, which often conflict. These judgments and their bases need to be stated explicitly and clearly. Accordingly, for the LADS study process, the Board took the position that the LADS study selection criteria and weighting should be defined clearly and that the transparency of the LADS study process should be improved (Cohon 1999a).

Unfortunately, the M&O chose not to quantify or otherwise state explicitly the value judgments it used for recommending the LADS study design. Because the values are not explicit, the Board—or anyone outside the process—cannot fully understand and evaluate the considerations applied in the selection. In its September 1999 letter (Barrett 1999), the DOE explained the bases for its acceptance, with conditions, of the M&O's recommendation. Although the letter addressed the Board's process concerns, its timing—seeming to come well after the tacit decision to proceed with EDA-II—did not increase the credibility of the LADS study process. In future decisions as important as LADS study, the DOE should make its explicit decision-making values and important policy bases known *well before* the decision is made.

2. The LADS Study Design

a. Above-Boiling and Below-Boiling Designs

In general, the closer that temperatures in the rock surrounding the repository can be kept to those of undisturbed rock, the lower the uncertainties about the movement of water in the rock and the better the performance of waste package materials. One key temperature is the boiling point of the water. Above this temperature, the water in rock pores and fractures will be vaporized; below this temperature, only a fraction will be vaporized.

Because of the significant uncertainties created by rock temperatures above the boiling point of the water in the rock, the Board does not believe that a strong-enough technical basis exists at this time to support adequately any repository design with postclosure rock temperatures above boiling. To use an above-boiling design as the basis for a site recommendation would require a significant gain between now and the time of site recommendation in the understanding of thermohydrologic processes and their effects on materials behavior. Although analytical and experimental work is under way and planned to improve understanding of the movement of water under conditions where temperatures of some of the rock surrounding the repository are above boiling, it is doubtful that the work could yield sufficiently better understanding in the next 2 years to establish an adequate technical basis for making a site-recommendation decision based on any above-boiling design.

The DOE's September letter (Barrett 1999) does not make clear to the Board which time for repository closure the DOE intends to use as the basis for its site recommendation. If the time of closure is 50 years after waste emplacement begins, some, if not all, of the emplacement drifts will have above-boiling temperatures shortly after closure, and the repository design would be considered an above-boiling design. If the time of closure is 125 years after waste emplacement begins, none of the emplacement drifts will have postclosure temperatures above boiling, and the design would not be considered an above-boiling design.

Although an adequate technical basis for above-boiling designs does not exist now and is not likely to for the next few years, the possibility remains that above-boiling designs eventually may prove superior to below-boiling ones. Thus, the DOE should continue its experimental and analytical work on above-boiling designs. What must be recognized, however, is that the issue of above-boiling design versus below-boiling design is unlikely to be resolved until well into the performance-confirmation period.

b. Drip Shield and Backfill

In the DOE's current design, the drip shield would be a curved self-supporting 15-mm plate of Grade 7 titanium that would be installed over the waste packages in segments just before repository closure. The length of drip shield segments would not be likely to correspond to the lengths of waste packages. The segments would be connected mechanically at time of placement to minimize water dripping between segments or backfill flowing between segments. Drip shields would be placed and connected remotely because of the high radiation fields in the emplacement drifts. The Board agrees that a drip shield offers the potential for improved safety performance and defense-in-depth. The Board understands how backfill might provide some protection for some drip shield designs. In its letter of July 9, 1999 (Cohon 1999a), the Board stated that it is looking forward to learning more about the enhanced performance predicted because of the addition of drip shields and backfill to the EBS design.

The drip shield segments likely can be built and inspected using technology that exists today. However, many questions still need to be answered. What are permissible leakage rates between drip shield segments for water and backfill? What is the design of the connection that will ensure leakage rates no higher than permissible? With what accuracy and precision do drip shield segments need to be placed to ensure proper connections? Similar questions apply to the placement of backfill. So far, the amount of additional information that will be developed about drip shields and backfill before the site-recommendation decision is unclear. This presents a dilemma. To take credit for the potential improved safety performance that a drip shield offers, one must have a solid technical basis or a very firm and well-grounded expectation that a solid technical basis could be developed by the time it is needed.

c. Design Evolution

The current waste package-EBS-repository design is an evolution of the *VA* design, which itself is an evolution of a design adopted in 1993, which in turn is an evolution of a design adopted in 1986. These design changes were based on improved knowledge, improved materials, more-complete study, or changed goals. A reasonable expectation is that this and future designs also will evolve as technology changes and as policies and perceived needs change. The current design and past designs were flexible enough to accept changes. Retaining this flexibility in future designs is important.

d. Other Aspects of the LADS Study Design

The Board understands that the 81-m spacing between emplacement drifts was based on the goal of having a large proportion of the rock between emplacement drifts remain below boiling after repository closure if closure occurs at 50 years after initiation of waste emplacement. Presumably, the spacing could be reduced if ventilation continues beyond 50 years. Even if closure occurs 50 years after waste emplacement begins, the spacing between the first-mined drifts would need to be significantly less than that between the last-mined drifts to obtain the same proportion of below-boiling rock between the drifts. This is because the period between emplacing waste in the first-mined drifts and emplacing waste in the last-mined drifts is approximately 24 years. Thus, the first-mined drifts would receive more than 20 additional years of ventilation than the last-mined drifts would receive.

Because of the decreased thickness of the waste package double wall in the LADS study design, the radiolysis issue has escalated in importance, particularly in the case of early repository closure (50 years after initial waste emplacement). The extent of potential radiolysis damage *inside* the waste package (from the interaction of radiation with residual water trapped inside the package) and its effect on performance also must be addressed. In particular, methods of limiting the amount of water trapped in waste packages, including canisters of waste packaged at power plants, must be studied.

The Board strongly believes that the LADS study should be a true study of alternatives to the *VA* design and not just a study of add-on enhancements. Underlying this belief is the Board's concern about the large uncertainties associated with the high temperatures of the *VA* design. It is unclear whether the DOE has been responsive to the Board's concern, because the design selected as a result of the LADS study may or may not result in drift-wall temperatures below boiling, depending on how it is implemented.

To simplify performance-confirmation activities during the preclosure period, the Board suggested that improved waste package shielding be among the design alternatives studied (Cohon 1999a). Although several self-shielded waste package designs were investigated as part of the LADS study process, they all resulted in high costs or in high waste package temperatures because of assumptions about heat removal from the waste package. The Board hopes that shielding will be investigated more thoroughly in the process of further defining and optimizing the LADS study design. In particular, the Board notes that radiolysis concerns can be eliminated by using self-shielded casks.

A key assumption for EDA-II is that the thermal power of any waste package will not exceed 11.8 kW at time of emplacement. To stay within the 11.8 kW limit, the EDA-II design would blend “hot” and “cold” assemblies together as necessary at a surface facility to be built at or near the underground repository. In addition, storage facilities would be needed nearby to accumulate hot or cold assemblies in advance of blending.

Blending and storage of spent fuel are commercially accepted and demonstrated technologies. All utilities practice wet storage in pools, and an increasing number practice dry storage. All of the latter use dry-storage containers that hold as many assemblies as or more than would be in EDA-II waste packages. The DOE’s planned use of blending at the repository would be only a slight extrapolation of current technology in that the DOE presumably would allow blending of assemblies from reactors from different sites. For practical reasons, utilities are essentially precluded from such blending.

In general, as the Board has pointed out previously, handling of spent-fuel assemblies should be minimized. Handling could be minimized, in part, by performing whatever blending is needed for disposal purposes at the time that assemblies are handled at reactor facilities or by shipping assemblies from reactors in such a sequence that storage and blending are minimized at the repository.

3. Waste Package Performance

The presentations on research of waste package degradation at the Board’s June and September meetings indicated that considerable valuable information on Alloy 22 is being collected. However, concern still exists about the effects of vapor-phase radiolysis. Resolving that concern may necessitate experimental and theoretical work on (1) how species created in the vapor phase could be captured and concentrated in liquid films and (2) how the concentrated species could exacerbate corrosion. The DOE has performed a significant amount of work to determine, or at least bracket, “worst case” environments that could exist on waste package surfaces. Performing the DOE’s suite of corrosion tests in environments that approximate both worst-case and more realistic situations is important.

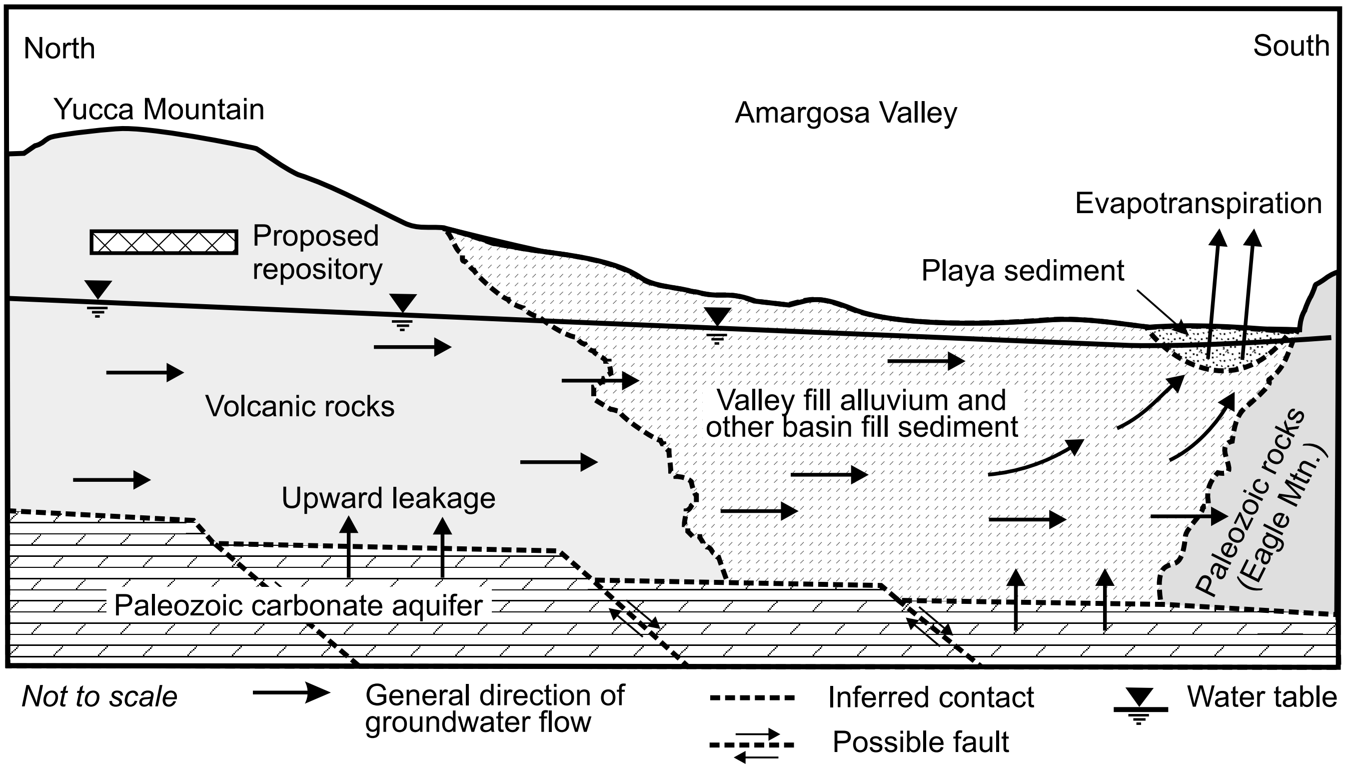
IV. The Board’s Review of Investigations in the Saturated Zone

A. Overview

Until recently, little attention was paid to the saturated zone (SZ) and its role in waste isolation at Yucca Mountain. This situation primarily arose because regulatory standards dating from the 1980’s determined compliance on the basis of radioactive releases to the accessible environment 5 km from the proposed repository. Release-based standards did not allow consideration of any dilution that might occur in the SZ. In addition, any delay in the transport of radionuclides in the SZ was not considered significant. Proposed Yucca Mountain-specific revisions (NRC 1999 and EPA 1999) of these earlier regulations have shifted the emphasis from release to dose and now consider a longer travel path (20 km) for the distance at which compliance will be determined. These revisions have resulted in a renewed interest in the properties of the SZ and the contributions that the SZ could make to an overall safety strategy and defense-in-depth.

The SZ lies at a depth of 500 m or more below Yucca Mountain. Its upper part consists of layers of volcanic tuff (the Upper Tram, Bullfrog, and Prow Pass formations) and is considered the main route for the

Figure 1–4. North-South Cross Section of SZ (after Czarnecki 1989)



transport of radionuclides. Beneath the tuff is an older carbonate aquifer that is connected to regional flow systems and is believed to be isolated from possible radioactive releases from Yucca Mountain. The volcanic tuff flow system is believed to trend southeast from Yucca Mountain to Forty Mile Wash and then south to Amargosa Valley. Somewhere along the way, the volcanic tuff grades into alluvium, which extends over large parts of Amargosa Valley. (A simplified geohydrologic cross section is shown in Figure 1-4.) The extent and nature of the alluvium could be very important in estimating dose because the alluvium may have a significant delaying effect on radionuclide transport.

B. The DOE's Scientific and Technical Work

In 1999, the DOE focused its investigation of the SZ on participating in the Nye County Early Warning Drilling Program (EWDP), which is discussed in greater detail in the next section; conducting independent investigations at several deep boreholes; and revising flow-and-transport models.

DOE-sponsored work in the EWDP has been devoted primarily to analysis of drill cuttings and water samples. Of particular interest have been tests devoted to determining the Eh and pH of water in the SZ. Reducing conditions could decrease the solubility of many radionuclides and slow down their transport considerably. Results thus far are mixed, and no consistent patterns have emerged.

SD-6 and WT-24 are deep boreholes drilled by the DOE to obtain information on the SZ. SD-6 is within the repository footprint, and WT-24 is just north of the footprint. At SD-6, preliminary results from aquifer testing show water-bearing fractures having very low permeability. One hypothesis is that the fractures encountered were secondary and not representative of the primary water-bearing fracture system. WT-24 was drilled to increase understanding of the large hydraulic gradient (LHG), a steep southerly dip in the regional water table. Perched water was encountered in this borehole before drilling was stopped at the water table. The DOE's current favored hypothesis is that the LHG exists but that it is not as steep as originally envisioned. The condition that caused the LHG also may cause some groundwater to flow eastward around the proposed repository. The DOE does not plan to resume drilling at WT-24 unless additional information is needed for site recommendation or licensing.

The DOE has devoted substantial effort to revising the models used to determine flow and transport in the SZ. The original models were subjected to a great deal of criticism and underwent last-minute changes in preparation for the *VA*. The new regional model, which sets the boundary conditions for the more localized site-scale model, has been upgraded from 3 layers to 15 layers; includes new estimates of groundwater discharge and evaporation; and takes into account new fault alignments, many of which were detected as a result of geophysical methods.

Fault control in the site-scale model also has been evaluated by scientists funded by the State of Nevada. On the basis of groundwater temperatures, these researchers maintain that groundwater flow beneath Yucca Mountain is controlled by faults and that groundwater could flow directly southward, avoiding much of Forty Mile Wash on its way to Amargosa Valley. Shorter travel times could affect the timing and size of dose estimates.

C. Nye County Early Warning Drilling Program

The EWDP is the main source of new data on SZ flow and transport between Yucca Mountain and Amargosa Valley. This work is an independent Nye County project that is supported financially by the DOE. Since the EWDP's inception in 1998, wells have been drilled at five sites close to Route 95, the highway separating Yucca Mountain and the Nevada Test Site (NTS) to the north from Amargosa Valley to the south. Lithologic, hydrologic, and hydrochemical tests are being carried out by scientists affiliated with Nye County. DOE-affiliated scientists also are conducting their own tests, primarily associated with hydrochemistry. All of this information will be used by the DOE to fill in a large data gap identified by many reviewers. Nye County scientists are still interpreting the results of their tests but can already point to the existence of a complex boundary between the volcanic aquifer and the alluvium. They also have observed high temperatures in some wells and a spike in measured gamma radiation (natural radioactivity) at one well. Various hypotheses have been proposed to explore the higher temperatures, such as upwelling of warmer water from the carbonate aquifer, but no conclusions have been reached.

The next phase of the EWDP involves drilling new wells and deepening others. One key component of this next phase will be establishing a "C-Well" type of complex in the alluvium. The original C-Well complex was set up to test flow-and-transport properties in the volcanic aquifer. Three wells were drilled near each other, and, among other experiments, tracers were introduced at one well and their arrival was monitored at the other wells. Current plans call for drilling three wells in the alluvium in Forty Mile Wash and conducting similar flow-and-transport tests. As indicated above, assumptions about the extent and nature of the alluvium along SZ flow paths can be very important in the calculation of dose.

D. The Board's Review Activities

The SZ was discussed at all Board meetings in 1999. In particular, a large amount of time was devoted to this topic in the June 1999 meeting in Beatty, Nevada. In addition to hearing from the DOE, the Board heard presentations from scientists supported by Nye County and from researchers supported by the State of Nevada. Immediately before the June 1999 meeting, Board members and staff visited several of the Nye County EWDP sites and Oasis Valley, a discharge area near the western end of the NTS. The visit was instructive in that the Oasis Valley area contains similarities to the Yucca Mountain flow system. A Board member also attended meetings related to SZ flow and transport around Devil's Hole (south of Yucca Mountain) and Death Valley (west of Yucca Mountain).

E. The Board's Conclusions and Recommendations

The Board recognizes the importance of the Nye County EWDP. It represents the largest and most critical source of data that will be used in determining the role of the SZ in any repository safety strategy and defense-in-depth analysis. All efforts should be made to ensure that the data will be usable by analysts. The Board is encouraged that efforts are being made to overcome previous problems of coordination between Nye County investigators and DOE-sponsored scientists.

In the next phase of the EWDP, the C-Well type of complex being planned for testing the flow-and-transport properties of alluvium is particularly important. The Board notes that the interface between the volcanic and alluvial aquifers is very complicated and urges that great care be taken in siting the test wells for studying the alluvium.

Much information on the SZ is being gathered. All of it needs to be integrated into a coherent model for flow and transport to prevent the kind of last-minute changes in SZ models that occurred just before the release of the *VA*.

Finally, unclear to the Board is whether the DOE has a strong understanding of the nature and significance of the LHG. A technically defensible analysis is needed to determine if the LHG should be included in the performance assessment and how it is treated.

V. The Board's Review of the DOE's Performance Assessment Activities

A. Overview

Total system performance assessment (TSPA) is the primary means by which the DOE will evaluate the ability of the proposed repository (natural and engineered components) to contain and isolate waste and meet regulatory standards. TSPA is a compilation of models of repository performance over time. Major iterations of TSPA for the Yucca Mountain site were carried out by the DOE and its contractors in 1991, 1993, 1995, and, most recently, 1998 (SNL 1992, SNL 1994, CRWMS 1995, and DOE 1998c). This last iteration (TSPA-VA) was conducted for the *VA*. The DOE is preparing a new iteration of TSPA (TSPA-SR) that will serve as the core technical component of a possible site recommendation and license application. Although past TSPA's have been used primarily for programmatic guidance—that is, helping determine critical issues and scientific priorities, the primary purpose of upcoming TSPA's will be to assess compliance with the the DOE's proposed siting guidelines, the EPA's proposed environmental standard, and the NRC's proposed licensing regulations.

B. The DOE's Scientific and Technical Work

The TSPA-VA formed the technical core of the *VA* and was the culmination of several years of effort. A summary discussion of the results at the Board's January 1999 meeting pointed out the value of the TSPA to the Yucca Mountain program (Van Luik 1999). Insights were gained into the relative importance of the various components of the repository system and their uncertainties, the determination of what may be achievable in system performance, and the determination of the strengths and weaknesses of the data, models, and assumptions. It was pointed out, however, that TSPA-VA should not be used to assess compliance with a regulatory standard, show defense-in-depth, assess the importance of small design changes, or determine site suitability. The DOE's view is that improvements now under way would allow future TSPA's to support a system suitability finding.

In conjunction with the development of the TSPA-VA, the DOE convened a Performance Assessment Peer Review (PAPR) panel. The panel issued its final report in 1999 and included some insightful comments about the TSPA (TSPA/PR 1999). Although the report stated that the TSPA-VA represents an advancement over previous TSPA's, it concluded, "… at the present time, an assessment of the future *probable behavior* [emphasis added] may be beyond the analytic capabilities of any scientific and engineering team." The panel's pessimism is attributed to the complexity of the repository system, the long time scales over which performance is to be described, the large and heterogeneous physical setting, and the nature of the data that exist now or that could be obtained in a reasonable time and at a reasonable cost. The panel also noted that these factors were compounded by the failure in many elements of the analysis to initiate and complete the necessary research, develop the appropriate models, and collect and apply the needed data and information. The panel pointed out many problems with specific models and data.

The panel suggested a different approach toward licensing. It argued that licensing does not require an estimation of probable behavior but does require reasonable assurance that the repository will comply with the applicable regulatory limits. The panel concluded that a somewhat different approach relying on a TSPA that, in some cases, makes use of simplified models and that is supplemented by carefully chosen bounding analyses, sensitivity analyses, and design changes could be effective during license application. Much additional data still would have to be collected, and some new analytical models still would have to be developed. In response to these comments, the DOE is trying to incorporate some of the panel's suggestions into the TSPA-SR. The DOE is to be commended for initiating the peer review and guaranteeing its independence.

Most of the DOE's TSPA efforts in 1999 were devoted to preparing an updated performance assessment for site recommendation, the TSPA-SR. The TSPA-SR will be based on information obtained up to August 1999. Subsequent iterations for the final version of the SR and for a possible license application will take more-recent investigations into account. Abstraction workshops for the TSPA-SR, begun in 1998, continued into 1999. The workshops, similar in principle to those conducted for the TSPA-VA, brought together scientists, engineers, and performance assessment analysts to define the work products needed for the TSPA-SR. These work products, called "analysis / model reports" (AMR's) and "process model reports" (PMR's), will define and justify the scientific and engineering assumptions and models that will be used in the TSPA-SR. More than 100 AMR's are planned. They cover a wide range of topics, from seepage calibration and model test data to dose-conversion factor analysis. The AMR's will be synthesized into nine PMR's for use in the TSPA. The PMR's cover generalized areas, such as the UZ, waste form degradation, and the biosphere. The AMR's and the PMR's will provide the technical basis for the TSPA-SR.

C. The Board's Review Activities

TSPA was discussed in all of the Board meetings in 1999 and in both of the Board reports issued that year. Board members and staff participated in the abstraction workshops.

D. The Board's Conclusions and Recommendations

The TSPA-VA represents a significant improvement in the DOE's effort to assess the performance of a proposed repository at Yucca Mountain. In comparison to previous iterations, the scope was broader, and the analysis was deeper. The results of investigations from the ESF, surfaced-based tests, laboratory investigations, and model studies were incorporated and integrated into the analysis. Clear text combined with figures that were very well thought out greatly improved the transparency of the analysis. In general, the TSPA-VA was very candid about the remaining uncertainties and their effect on any conclusions that were drawn. As indicated above, the DOE also was candid about the uses and possible misuses of TSPA-VA. Presentations to the Board indicate that the DOE is taking many of the recommendations of the PAPR panel to heart. Many models are being revised, and some new ones are being proposed.

However, judging the realism of the "bottom-line" dose estimates in the TSPA-VA is difficult. Some of the assumptions and models used, such as the SZ model, may be conservative (erring on the side of safety), while others, such as the assumption of cladding credit, may be nonconservative. (See TSPA / PR 1999 as well.) For the next iteration of TSPA, additional data for both the natural and the engineered systems will be needed to arrive either at a more persuasive estimate of repository performance or a judgment of the assessment's conservatism with respect to a safety standard. The kinds of data required have been specified in recent Board reports (e.g., NWTRB 1998). In its November letter, the Board described the challenges associated with model validation (Cohon 1999b). These challenges include the preparation of an adequate database, the need to develop multiple and independent lines of evidence, and the problems in extrapolating short-term data to the long periods of time needed to assess repository performance.

In its report summarizing 1996 activities (NWTRB 1997) and in its comments on the *VA* (NWTRB 1999b), the Board pointed out the need to supplement TSPA with other measures to make a robust safety case. In the *VA*, the DOE recognized the need for such supplementary measures, including a demonstration of defense-in-depth and insights from natural and man-made analogs. The Board again calls the DOE's attention to the supplementary measures that the DOE itself and the Board have described and recommends that they be pursued vigorously.

VI. The Board's Review of the DOE's Transportation Activities

Because of a reduction in funding, the DOE dramatically reduced its transportation activities in 1999. However, in 1999, Board members and staff attended several DOE-sponsored meetings related to transportation and met with the staff of Oak Ridge National Laboratory (ORNL). The main objective of the trip to ORNL was to see DOE's TRANSCOM system, a shipment-tracking system that allows constant monitoring of a shipment's location. It also permits communication between the truck or train and the people monitoring the shipment. Shipment tracking will be an integral part of the DOE's plans for ensuring safe and secure transportation of spent nuclear fuel and high-level radioactive waste.

To determine how quality assurance is incorporated in the manufacturing process and to understand industrywide production capacity in anticipation of a major shipping campaign, Board staff observed a conference of cask manufacturers. Participants indicated that effective quality assurance measures are available in both the design and manufacturing processes and that sufficient capacity could be developed for designing and building transportation casks for the DOE's proposed shipping campaign

The Board also is reviewing the DOE's draft environmental impact statement (EIS) for Yucca Mountain to determine if transportation safety issues are addressed adequately.

VII. International Activities

Members of the Board and staff participated in several international meetings and trips in 1999. In contrast to past international trips, all of the international trips made by Board members and staff in 1999 were paid for in part by organizations in the countries visited.

In March, four representatives from the Board participated in the Swedish National Council for Nuclear Waste (KASAM) three-year review of the Swedish Nuclear Fuel and Waste Management Company's (SKB) 1998 research program. SKB has the responsibility under Swedish law for managing all spent nuclear fuel and implementing a program for the permanent disposal of the fuel. KASAM's responsibility is to review the SKB program from both a scientific and technical viewpoint and a societal viewpoint. Present at this meeting were representatives from all of the key Swedish agencies involved in the nuclear waste program.

Following the review, a member of the Board and a staff member traveled to the municipality of Oskarshamn, which is in southeastern Sweden. Oskarshamn is one of a number of municipalities that have volunteered to participate in the first of several phases of a feasibility-study process aimed at designating a site for a permanent repository. The municipality already is host to a number of nuclear facilities, including nuclear power plants, the facility for storing spent nuclear fuel, a pilot encapsulation facility for a potential repository, and Äspö, a hard-rock laboratory that is used to conduct research for spent fuel disposal.

In June, two representatives of the Board participated in a study conducted by the European Union of current and future trends in nuclear expertise. Although the study focused on Europe's nuclear community, the Board representatives provided information, reports, and insights based on their experiences in the United States. The meeting was held in Brussels, so the opportunity was used to meet with representatives of the Belgian and French governments and private companies responsible for managing the storage and disposal of spent nuclear fuel and high-level waste.

Also in June, a member of the Board and a staff member attended VALDOR, a conference sponsored mainly by the European Union on the role of values in risk assessment. Although the meeting examined a range of risky technologies, the primary focus was on how societal values might be incorporated properly in performance assessments.

In October, a representative of the Board was invited to attend an international seminar on issues surrounding the possible retrieval of high-level radioactive waste or spent nuclear fuel from a repository. Arranged by KASAM, in cooperation with the International Atomic Energy Agency, the seminar was held near Stockholm, Sweden. Most countries involved in work to dispose of nuclear waste have concluded that the generation that derives the benefits from nuclear power should solve the nuclear waste problem and not pass it on to future generations. Recently, this belief has been reexamined to some extent by those involved in reviewing the waste isolation concepts in some countries, including Canada, France, Germany, the United Kingdom, and Sweden.

One member of KASAM, for example, has suggested consideration of a new principle that states that future generations should have the freedom to make their own decisions on the use of resources and their own value judgments on safety. In the Netherlands, the phrase “rolling present” has been coined to describe the ongoing decision of each generation on whether to close or keep open an underground waste storage facility. KASAM’s seminar focused on discussing these two principles as well as on hearing from experts in different national approaches to the retrieval of waste and other technical, moral, ethical, and cost issues involved in developing repositories where the waste could be recovered.

In October, a small delegation of Board and staff accepted a long-standing invitation and traveled to China. The purpose of the trip was to meet with representatives of China’s nuclear waste disposal program and to visit and provide expert advice on the characterization of their proposed repository site, the Beishan site, which is in the Gobi desert in Gansu Province in northwest China.

In November, representatives of the Board attended the U.S. Secretary of Energy’s International Conference on Geologic Repositories in Denver, Colorado, and an international workshop held by the National Academy of Sciences (NAS) Board on Radioactive Waste Management in Irvine, California. The workshop, titled “Disposition of High-Level Radioactive Waste Through Geological Isolation: Development, Current Status, and Technical and Policy Challenges,” was organized as a follow-up to a similar meeting held by the NAS in 1990.

VIII. Evaluation of the Board’s Performance During 1999

The Board believes that measuring its effectiveness by directly correlating improvements in the DOE program with Board actions and recommendations would be ideal. However, the Board has no implementing authority, so it cannot compel the DOE to comply with its recommendations. Consequently, a judgment about whether a specific recommendation had a positive outcome for the DOE program is, in most cases, (a) subjective and (b) an imprecise indicator of Board performance because implementation of Board recommendations by the DOE is outside the Board’s direct control. Therefore, to measure its performance in a given year, the Board has developed the following performance measures for each annual performance goal.

1. Whether the reviews, evaluations, and other activities undertaken under the auspices of the goal were completed.

2. Whether the results of the reviews, evaluations, and other activities were communicated in a timely, understandable, and appropriate way to Congress and the Secretary of Energy.

If both measures are met, the Board’s performance in meeting the annual goal will be judged effective. If only one measure is met, the Board’s performance in achieving that goal will be judged minimally effective. Failing to meet both performance measures, without sufficient and compelling explanation, will result in a judgment that the Board has been ineffective in achieving that performance goal.

On the basis of these performance measures and the evaluation included in the appendices to this report, the Board’s performance for fiscal year 1999 was found effective. For a more detailed discussion of how the Board evaluated itself, see Appendix E.

Abbreviations and Acronyms

AAR American Association of Railroads

AMR analysis / model report

Board U. S. Nuclear Waste Technical Review Board

CFR *Code of Federal Regulations*

CFu Crater Flat undifferentiated unit

CHn Calico Hills nonwelded unit

^{36}Cl chlorine-36

CRWMS Civilian Radioactive Waste Management System

DOE U.S. Department of Energy

DOT U.S. Department of Transportation

EBS engineered barrier system

ECRB enhanced characterization of the repository block

EDA II Enhanced Design Alternative II

EIS environmental impact statement

EPA U.S. Environmental Protection Agency

ESF exploratory studies facility

EWDP Early Warning Drilling Program

HAZ heat-affected zone

HLW high-level radioactive waste

KASAM Swedish National Council for Nuclear Waste

km kilometer

kW kilowatt

LADS License Application Design Selection

LHG large hydraulic gradiant

m meter

mm millimeter

m^3 cubic meter

M&O DOE's management and operating contractor

NAS National Academy of Sciences

NRC U.S. Nuclear Regulatory Commission

NTS Nevada Test Site

NWPA Nuclear Waste Policy Act

NWPAA Nuclear Waste Policy Amendments Act

NWTRB U.S. Nuclear Waste Technical Review Board

OCRWM Office of Civilian Radioactive Waste Management, U.S. Department of Energy

ORNL Oak Ridge National Laboratory

PA performance assessment

PAPR Performance Assessment Peer Review

PMR process model report

PTn Paintbrush Tuff nonwelded unit

PWR pressurized-water reactor

SCC stress-corrosion cracking

SKB Swedish Nuclear Fuel and Waste Management Company

SNL Sandia National Laboratory

SR site recommendation

SRCR *Site Recommendation Consideration Report*

SZ saturated zone

TCw Tiva Canyon welded unit

TSw Topopah Spring welded unit

TSPA total system performance assessment

TSPA-SR total system performance assessment-site recommendation

TSPA-VA total system performance assessment-viability assessment

USGS U.S. Geological Survey

UZ unsaturated zone

VA *Viability Assessment* (DOE report)

Glossary

The following list of terms has been compiled to aid in the reading of this report. It is not meant to be a formal glossary or to have the completeness of a dictionary.

accessible environment. The earth's surface and the rock more than 5 kilometers beyond the repository.

alluvium. Clay, silt, sand, gravel, or similar material deposited by running water.

analog. A thing or part that is analogous. As used in this report, a phenomenon that can provide information on or add to understanding of aspects of repository performance. Analogs are of two types: natural and anthropogenic. Natural analogs occur through natural phenomena. Anthropogenic analogs result from human activity.

areal mass loading. The concentration of emplaced spent fuel, averaged over the area of the repository and expressed in kilograms per square meter or in metric tons per acre.

backfill. Solid materials placed in excavated areas underground to fill voids (e.g., crushed tuff).

barrier. Something that prevents or retards the passage of radionuclides toward the environment.

canister. The structure surrounding a waste form (e.g., high-level waste immobilized in borosilicate glass) that facilitates handling, storage, transportation, or disposal. Before being emplaced in a repository, the canister may be placed in a disposal container.

characterization. The process of collecting information necessary to evaluate the suitability of a region or site for geologic disposal. Data from characterization also will be used during the licensing process.

chlorine-36 (^{36}Cl). A long-lived radioactive isotope of chlorine produced by irradiation of natural chlorine, argon, or other materials by cosmic rays or neutrons. Atmospheric testing of nuclear weapons in the 1950's temporarily increased concentrations of chlorine-36. The resulting "bomb pulse" levels of chlorine-36 can sometimes serve as a tracer to determine how precipitation from the 1950's has moved through soil and rocks, such as those present at Yucca Mountain.

cladding. Thin metallic material that encases nuclear fuel.

container. A receptacle used to hold radioactive waste (usually spent fuel).

corrosion-resistant materials. Materials that fail primarily because of localized corrosion and that tend to fail more slowly than corrosion-allowance materials.

defense-in-depth. Incorporation of multiple barriers in the design of a repository to make the performance of the overall system less susceptible to the unexpected failure of any individual barrier.

dilution. Reducing the concentration of radioactive materials that might be released from a repository.

disposal. Isolation of radioactive wastes from the accessible environment involving no foreseeable intent of recovering them. Isolation occurs through a combination of engineered and natural barriers rather than through human action.

dose. See **radiation dose**.

drift. A near-horizontal excavated passageway through the earth; a tunnel.

drip shields. Barriers placed over or around waste packages to divert water from the packages.

east-west cross drift. A small exploratory tunnel across the proposed repository for enabling scientists to examine the geologic and hydrologic conditions.

Eh. Oxidizing or reducing potential.

emplacement drift. Tunnels in which radioactive waste will be placed in the repository.

engineered barrier system (EBS). The constructed components of a disposal system designed to slow down or prevent the release of radionuclides from the underground facility. The EBS includes the waste form, the waste package, materials placed over and around the waste package, and barriers used to seal penetrations (e.g., shafts and ramps) directed into and within the underground facility.

enhanced characterization of the repository block (ECRB). DOE's proposal for an east-west exploratory tunnel containing three test alcoves and two boreholes to provide more preliminary information on the repository block.

environmental impact statement (EIS). A detailed written statement for supporting a decision on whether to proceed with major U.S. Government actions affecting the quality of the human environment.

expert judgment. An evaluation based on an assessment of data, assumptions, criteria, or models by one or more experts in a field.

exploratory studies facility (ESF). An underground facility constructed for performing exploration and testing to determine the site's suitability to host a geologic repository.

fault. A plane in the earth along which differential slippage of the adjacent rocks has occurred.

flow path. The direction that underground water and any contaminants it may contain flow.

fluid inclusion. Small droplets of fluid that are trapped in a growing crystal or in a crystal fracture.

fracture. Any break in a rock (i.e., a crack, a joint, or a fault), whether or not accompanied by displacement.

fracture flow. Flow through the fractures in a given medium, such as through rock or soil.

geochemistry. Study of the amounts and distribution of chemical elements in minerals, rocks, soil, water, and the atmosphere. Geochemistry at the Yucca Mountain site is concerned primarily with the potential migration of radionuclides to the accessible environment. Geochemists are studying the chemical and physical properties of the minerals, rocks, and waters that might affect the migration of radionuclides from a repository.

geologic repository. A system for disposing of radioactive waste in excavated geologic media, including surface and subsurface areas of operation and the adjacent part of the natural setting.

groundwater. Water that exists or flows beneath the land surface.

high-level waste. Highly radioactive material from reprocessing spent nuclear fuel, including liquid waste produced directly in reprocessing or any solid material derived from such liquid waste. Any other highly radioactive material that the U.S. Nuclear Regulatory Commission determines requires permanent isolation by disposal in a geologic repository.

hydrogeology (hydrology). The science dealing with subsurface water and with related geologic aspects of surface water. At the Yucca Mountain site, emphasis is placed on the study of liquid transport through the rock matrix and fractures. Groundwater is a primary means by which radionuclides could be transported from the repository to the accessible environment.

infiltration. Water entering soil or rock after precipitation rather than becoming runoff into rivers, streams, ponds, etc. The terms "infiltration" and "net infiltration" also are used to refer to water that penetrates deeply into soil or rock (beneath plant root zones) rather than returning to the atmosphere by evapotranspiration.

invert. The part of the bottom of a tunnel that has been made level by adding materials.

license application. A document submitted to the U.S. Nuclear Regulatory Commission containing general information and a safety analysis for a nuclear reactor, a geologic repository, or an interim storage facility for spent nuclear fuel and high-level radioactive waste.

License Application Design Selection (LADS). A focused effort, arising from the design-alternative studies conducted for supporting the viability assessment, to select the final repository design for the license application.

lithophysal, nonlithophysal. Lithophysal and nonlithophysal zones denote the relative abundance of lithophysae found in different rock strata. Lithophysae, sometimes called "stone bubbles," are cavities in silicic volcanic rock that are formed, soon after the volcanic rocks are deposited, because of the presence of vapors under very high pressure.

matrix. In hydrology, the solid framework of a porous system.

nonwelded tuff. A tuff that has not been hardened and welded together by intense temperature and pressure and that contains fewer fractures than welded tuff does.

Nuclear Waste Policy Act (PL 97-425). The federal statute enacted in 1982 that established the Office of Civilian Radioactive Waste Management in the U.S. Department of Energy and defined its mission for developing a federal system for the management and geologic disposal of commercial spent nuclear fuel and other high-level radioactive wastes as appropriate. The Act also specified other federal responsibilities for nuclear waste management, established the Nuclear Waste Fund to cover the cost of geologic disposal, authorized interim storage until a repository is available, and defined interactions between federal agencies and states, local governments, and Indian tribes.

Nuclear Waste Policy Amendments Act of 1987 (PL100-203). The legislation that amended the Nuclear Waste Policy Act to limit repository site-characterization activities to Yucca Mountain, Nevada; establish the Office of the Nuclear Waste Negotiator for seeking a state or an Indian tribe willing to host a repository or a monitored retrievable storage facility; create the Nuclear Waste Technical Review Board; and increase state and local government participation in the waste management program.

passive layer. A microscopically thin passive film on the surface of an alloy that separates the alloy from the surrounding environment.

perched water. Groundwater separated from an underlying body of groundwater by an unsaturated zone.

percolation. As used by the Yucca Mountain Project, water moving from the surface through the location where a repository would be built. At specific points within the proposed repository location, percolation may differ from (net) infiltration flux if fractures or other geologic structures enhance, impede, or divert the flow of water as it moves down through the mountain.

performance assessment (PA). An analysis that predicts the behavior of an entire system or a part of a system under a given set of conditions on the basis of an assumed measure of performance.

pH. Alkalinity or acidity (e.g., of water).

postclosure. The time after the closure of the repository.

preclosure. The time before the closure of the repository.

radiation dose. The amount of energy deposited in a unit of mass of a material. Any of several modified doses, including dose equivalent and effective dose, that more closely approximate the biological harm to humans from exposure to ionizing radiation.

radionuclide transport. The movement of radionuclides, generally as dissolved solids or gaseous forms, through a rock formation.

repository. See **geologic repository**.

repository block. The part of Yucca Mountain in which placement of the proposed repository is being considered.

retardation. The physical or chemical process that causes some dissolved radionuclides to move more slowly than the water they are dissolved in.

saturated zone (SZ). The part of the earth's crust in which all voids are filled with water under pressure at least as great as atmospheric pressure.

shrinkfitting. Joining (or mating) layers of metal by using heat to expand the outer shell, inserting the inner shell, and allowing the outer shell to cool around the inner shell.

site assessment. The full range of activities needed to evaluate the suitability of the Yucca Mountain site, including site characterization; laboratory research; performance assessment; and design of the repository, waste packages, and engineered barriers.

site characterization. See **characterization**.

sorption. The binding, on a microscopic scale, of dissolved molecules or atoms on mineral surfaces in contact with fluid. The sorption of dissolved radionuclides can lead to their retardation.

spent nuclear fuel. Fuel that has been withdrawn from a nuclear reactor after irradiation, the constituent elements of which have not been separated by reprocessing.

stress-corrosion cracking (SCC). A form of environmentally induced cracking. Local moderate-to-high and localized corrosion combine to cause the rapid propagation of a crack.

structural geology. Study of the deformational features of rocks induced by processes such as folding, faulting, and igneous activity.

suitability determination. The formal recommendation by the U.S. Department of Energy to the President on whether the Yucca Mountain site can safely host a repository for high-level waste.

thermal load. The amount of heat produced by emplaced waste and affecting the near field and the overall repository material, including geophysical and engineered barriers (usually measured in kilowatts per acre).

total system performance assessment (TSPA). Analyses undertaken by the U.S. Department of Energy to assess the ability of the potential repository at Yucca Mountain to provide long-term waste isolation.

transparent (performance assessment). Easy to detect or perceive. Using clear language and easily understood concepts or assumptions to arrive at credible, traceable, and logical conclusions.

tuff. A rock composed of compacted volcanic ash. It is usually porous and often relatively soft.

unsaturated zone (UZ). Geologic formations located above the regional groundwater table. Also called the "vadose zone."

***Viability Assessment* (*VA*).** A congressionally mandated report that the Secretary of Energy provided to the President and Congress in 1998. It includes repository and waste package designs, a total system performance assessment, a license application plan, and estimates of repository cost and schedule.

waste form. Radioactive waste materials and any encapsulating or stabilizing matrix. Examples include used reactor fuel elements and borosilicate glass "logs."

waste package. The waste form, any fillers, and any containers, shielding, packing, or other absorbent materials immediately surrounding an individual waste container.

water table. An underground boundary below which the rock pores are completely filled with water and above which they are only partly filled with water.

welded tuff. Rock made of volcanic ash that has been hardened and welded together by heat, pressure, and possibly the introduction of cementing minerals. Welded tuff contains more fractures than nonwelded tuff does.

zeolites (zeolite minerals). White, faintly colored, or colorless silicate minerals characterized by their easy and reversible loss of water and their high absorption capacity for dissolved metal ions in water.

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