U.S. NUCLEAR WASTE TECHNICAL
REVIEW BOARD

1997
Findings and Recommendations

Report to

The U.S. Congress and The Secretary of Energy

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Executive Summary

In 1997, the U.S. Department of Energy's (DOE) efforts relating to the disposal of spent nuclear fuel and high-level radioactive waste focused on the upcoming viability assessment (VA). As required by the Energy and Water Appropriations Act for fiscal year 1997, the Secretary of Energy is to provide the President and Congress with a VA of the Yucca Mountain site by September 30, 1998. It will include four elements: (1) the preliminary design concept for the critical elements for the repository and waste package; (2) a total system performance assessment (TSPA) based on the design concept and on the scientific data and analysis available by September 30, 1998, and describing the probable behavior of the repository in the Yucca Mountain geological setting in relation to the overall system performance standards; (3) a plan and a cost estimate for the remaining work required to complete a license application; and (4) an estimate of the cost of constructing and operating the repository in accordance with the design concept.

For the first element, design of repository and waste package critical elements, the program made progress in several different areas in 1997, including refinement of the designs for the surface and underground facilities of the repository and for the waste package; further integration of DOE-owned spent fuel into disposal plans; continued evaluation of criticality-control issues; and improved integration of engineering and performance assessment. Other areas continue to need further attention. For example, the DOE needs to explore more-robust engineered barrier systems and thoroughly explore different integrated repository and waste package designs that may hold the promise of better performance, lower cost, or simpler operations. Some of these alternative designs include the possible use of smaller emplacement drifts than currently envisioned, ventilation of emplacement drifts both before and after repository closure, smaller waste packages, and a waste package design based on two corrosion-resistant materials rather than one.

The DOE's most extensive effort in 1997 was devoted to the second element of the VA, the TSPA. TSPA is a predictive-computational model of repository performance and is the principal method for evaluating the ability of the proposed repository to contain and isolate waste. The TSPA will consist of two parts: (1) a "base case" calculation that concentrates on probable (i.e., expected) performance and (2) a series of sensitivity tests that will look at "What if?" scenarios for alternative input parameters and design features and for disruptive events, such as volcanic activity and earthquakes. During 1997, two series of extensive workshops were held. The first series, abstraction and testing, brought together scientists, modelers, and analysts to better define which processes are important and how to capture them for use in the TSPA. The second series involved eliciting expert judgment (primarily from outside the Yucca Mountain project) on the uncertainty associated with different predictive models and data sets. The DOE also formed an external TSPA peer review panel, which has begun providing the DOE with a strong and independent perspective on the developing TSPA. The Board supports the DOE's continuing effort to pay close attention to the panel's comments.

In 1997, the Board devoted relatively less effort to the last two elements of the VA, (3) a plan and a cost estimate for the remaining work required for license application and (4) an estimate of the cost of repository construction and operation, than to the first two elements. The Board believes, however, that the remaining work should include vital ongoing technical activities, such as the new plan for enhanced characterization of the repository block, long-term corrosion tests, and the drift-scale thermal test discussed below.

There was some activity in regulations and standards. The DOE issued draft revisions to siting guidelines, which will be used to determine the suitability of the Yucca Mountain site. The draft guidelines rely heavily on the use of a single standard based on TSPA rather than the multiple criteria that existed in the past. Although the Board believes that this is a step in the right direction, it made several recommendations to the DOE in 1997 that are designed to increase the clarity, believability, and acceptability of conclusions based on performance assessment. The Board strongly believes that the principle of defense-in-depth through the use of multiple barriers must be preserved and demonstrated. In the absence of environmental standards (being developed by the U.S. Environmental Protection Agency), the DOE has developed an interim performance measure. The Board feels that the interim measure is appropriate except for the exclusion of children from the hypothetical group for which repository-related doses will be calculated.

Transportation of spent fuel continued to be a matter of interest in 1997. The Board devoted a meeting to this topic and heard from the DOE and the two agencies that share regulatory responsibility in this field, the U.S. Department of Transportation and the U.S. Nuclear Regulatory Commission. As a result of the meeting, the Board drew two conclusions: (1) the existing capability to transport spent fuel is small, and much preparatory work needs to be done before fuel can be transported in large quantities; and (2) additional measures, such as the use of dedicated trains and full-scale testing of transportation casks, may enhance the perceived level of safety. The Board continues to believe that the risks associated with transporting spent fuel are low.

During 1997, the Board visited the field and heard presentations on what would happen to radioactive waste when it reaches the water table below Yucca Mountain. The presence of highly fractured rock suggests that the flow of groundwater—and any radioactive waste that it may transport—may be channeled within the more transmissive zones of fractured rock. Some dilution or mixing with radionuclide-free water will occur, but its extent is difficult to predict, at least in part because of the hydrologic data limits beyond Yucca Mountain. Perhaps a greater source of dilution may be mixing at a wellhead when groundwater is withdrawn from an aquifer for human use. Once the well water is withdrawn, the fate of any transported radionuclides as they enter the food chain and potentially cause radiation doses to humans must be estimated. The use of generic rather than site-specific data in models used to calculate the transfer of radionuclides through the food chain may cause large uncertainties in estimated radiation doses.

The exploratory studies facility (ESF) was completed on April 25, 1997. This 7,877-meter (m) tunnel (25,800 ft) continues to provide a wealth of data. In the Board's view, there are a number of lessons to be learned from the engineering side of the effort. They include the need to emphasize performance in construction contracts and to make more use of industry expertise. The DOE is making effective use of an engineering consulting board in achieving this objective. The Board's earlier recommendation that a small-diameter east-west exploratory tunnel be driven across the proposed repository block was accepted by the DOE. The tunnel is part of a new effort called "enhanced characterization of the repository block." Aside from the tunnel, this effort will include three test alcoves along the tunnel and two new surface boreholes. The DOE is expeditiously pursuing the excavation of the tunnel, and valuable information from mapping and limited testing may be available before the scheduled delivery date of the VA.

A series of thermal tests in the rock in and around Yucca Mountain were completed or initiated during 1997. The main purpose of the tests is to determine the mechanical, hydrologic, and chemical responses to the elevated temperatures that will be caused by the emplacement of radioactive waste. The tests include the surface-based large-block test and the ESF-based single-heater and drift-scale tests. The results from the completed first two short-term tests are providing valuable information on the complexity of the hydrologic response. The drift-scale test, begun ahead of schedule, is a massive test involving a 47.5-m-long (156 ft) test area, tens of heaters, and thousands of sensors and is scheduled to last 8 years. The data from this test will substantially improve our understanding of thermal response. The DOE is commended for planning and constructing this facility.

The DOE is receiving valuable advice from outside sources, such as the TSPA peer review panel and the engineering consulting board. Another type of external input—from panels of experts from whom judgments are formally elicited—also is proving very useful. During the last 2 years, the DOE convened seven expert panels covering topics ranging from volcanism to unsaturated zone hydrology to waste package degradation. Most, but not all, of the panels were assembled for the TSPA.

In addition to supplying information that can be used directly for performance assessment and design, the panels have provided important insights on scientific models, design assumptions, and the importance, or lack thereof, of different hypotheses. To make full and effective use of this input, the DOE needs to articulate how it intends to aggregate the views of multiple experts and how the individual views of the experts will be treated in performance assessment. The DOE also should address the potential problems posed by receiving input on some issues from only a small number of the experts who were asked, and should consider developing guidelines on how it will treat the results of an expert elicitation in light of new data and analyses.

Finally, the Board's marked change in membership during 1997 should be noted. In the early part of the year, President Clinton appointed eight new members to the Board and designated Dr. Jared L. Cohon, one of the three continuing members, chairman.

Recommendations of the Board

Specific recommendations made in this report are presented below. The Board makes these recommendations in the belief that they will help the DOE achieve its goal of successfully designing and implementing a program for safely and efficiently managing the nation's spent fuel and high-level radioactive waste.

- The Board views the DOE's work on alternatives to the reference design as a vital element in the repository program. Although much of this work will be carried out subsequent to the VA, the DOE should consider including, in the VA, cost estimates of alternative repository design concepts and sensitivity studies showing the effects of these alternative design concepts on long-term repository performance. Work on alternative repository designs should be started now, even if it cannot be included in the VA.

- The DOE should estimate *and disclose* the likely variation in doses for alternative candidate critical groups characterized by different locations, ages, and lifestyles. In particular, potential doses to children should be compared with doses to adults within each candidate group.

- The DOE should evaluate the need for site-specific data for supporting the biosphere modeling needed for license application, especially soil-to-plant transfer factors. The evaluation should include an estimate of the length of time over which measurements of such parameters would be needed to produce a reliable data set. Plans for obtaining the necessary data should be developed now.

- The DOE should make full and effective use of the expert elicitations, both as direct input to performance assessment and design and for the technical insights provided. The DOE should provide a rationale for the way it intends to aggregate the views of different experts and how the individual views of the experts will be treated in performance assessment. The DOE also should consider developing guidelines on how the results of expert elicitations will be treated in light of new data.

Introduction

The federal government has been responsible for the permanent disposal of high-level radioactive waste and spent nuclear fuel since the beginning of commercial nuclear power nearly half a century ago. The responsibility became formal national policy in the Nuclear Waste Policy Act of 1982 (NWPA), which declared "… the Federal Government has the responsibility to provide for the permanent disposal of high-level radioactive waste and such spent nuclear fuel as may be disposed of in order to protect the public health and safety and the environment …" The NWPA designated the U.S. Department of Energy (DOE) the agency for carrying out the federal responsibility.

There is a broad international consensus that high-level radioactive materials can be disposed of safely in mined geologic repositories. Mined geologic disposal has been and continues to be U.S. policy and is a central tenet of the NWPA. A combination of engineered and natural barriers would isolate wastes for many thousands of years from the parts of the environment that are accessible to humans. During that period, radioactive decay would reduce the hazard of the wastes, and natural processes would disperse the wastes and delay their transport so that any releases to the accessible environment would be at levels below regulatory concern. The NWPA was amended in 1987 to restrict site-characterization studies to a single candidate site at Yucca Mountain in Nevada. Studies of the Yucca Mountain site as a potential location for a deep geologic repository have dominated the DOE's activities related to disposal of civilian spent fuel and high-level waste since 1987.

Spent nuclear fuel and high-level radioactive waste are long-lived and hazardous to humans and the environment. Predicting a repository's ability to isolate radioactive materials for thousands of years is a major technical challenge. Detailed, expensive studies of the Yucca Mountain site are designed to meet that challenge. Of utmost importance is that the right studies are carried out, the scientific work is of the highest quality, and the quality of the work can be demonstrated effectively in an adversarial licensing process. Only if the Yucca Mountain site is adequately studied by using state-of-the-art scientific techniques can scientists, engineers, regulators, and the public—especially the citizens of Nevada—develop confidence that a repository will be safe for the thousands of years that spent fuel and high-level waste will remain hazardous.

The U.S. Nuclear Waste Technical Review Board (Board) is an independent federal agency created by statute and charged with evaluating the technical and scientific validity of the DOE's activities under the NWPA. A full Board consists of 11 members who are nominated by the National Academy of Sciences (NAS) and appointed by the President.

The Board is required to submit its findings, conclusions, and recommendations to the Congress and the Secretary of Energy at least twice each year. The Board's first report (NWTRB 1990a) was released in March 1990. Current Board reports are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402. Current and past Board reports are available from the Board's office in Arlington, Virginia. Board reports also are available at the Board's Web site, www.nwtrb.gov.

This report reviews program developments and Board activities during 1997. In a general overview of the entire program, Chapter 1 summarizes progress during 1997, particularly in characterizing the Yucca Mountain site. There were many noteworthy accomplishments in 1997. In particular, the nearly 8-kilometer (km)-long exploratory studies facility (ESF) was completed in April 1997, culminating several years of excavation. This tunnel, which descends to the level of the proposed repository and would become the eastern edge of the proposed repository, already has been the source of invaluable geologic and hydrologic data. Also in 1997, the DOE decided to bore a drift across the proposed repository at a level approximately 10 meters (m) above it. Construction of the drift had started by the end of the year. The Board is very pleased because the drift should produce valuable data within the repository block that are necessary for a technically defensible determination of the suitability of the Yucca Mountain site for a repository.

No matter how robust the containers holding waste in a repository are, they will eventually corrode, allowing waste to be transported to the water table some 300 m below the repository. Chapter 2 reviews hydrologic issues in the movement of waste in the saturated zone (the zone at and below the water table) to the accessible environment.

Also notable in 1997 was that extensive input from outside experts was brought into many of the DOE's technical program areas through a rigorous and disciplined process know as "expert elicitation." Chapter 3 discusses the expert elicitations held in 1997 and the important insights developed.

Chapter 1
Program Overview

I. Progress in the Viability Assessment

As required by the 1997 Energy and Water Development Appropriations Act (U.S. Congress 1996), the Secretary of Energy is to provide to the President and Congress a viability assessment (VA) of the Yucca Mountain site no later than September 30, 1998. The VA shall include the following elements:

1. The preliminary design concept for the critical elements for the repository and waste package. (The DOE calls this design the "reference design.")

2. A total system performance assessment (TSPA) based on the design concept and on the scientific data and analysis available by September 30, 1998, and describing the probable behavior of the repository in the Yucca Mountain geological setting in relation to the overall system performance standards. (The abbreviation for this element is TSPA-VA.)

3. A plan and a cost estimate for the remaining work required to complete a license application.

4. An estimate of the cost of constructing and operating the repository in accordance with the design concept.

As soon as the VA becomes available, the Board intends to conduct a rapid and thorough review of the parts of the VA that fall within the Board's purview. Because the Board is a technical body whose members represent scientific and engineering disciplines, its review will concentrate on the technical and scientific aspects of the VA. Essentially, this means that the review will focus primarily on elements 1 and 2 of the VA.

The four meetings of the full Board preceding the scheduled delivery date for the VA will prepare the Board to review the VA. The Board's June 1997 meeting in Las Vegas covered the hydrology of the unsaturated zone (the part of Yucca Mountain above the water table). The Board's October 1997 meeting in Fairfax, Virginia, covered the repository and waste package design and repository operations. The January 1998 meeting in Amargosa Valley, Nevada, covered the hydrology of Yucca Mountain and surroundings below the water table (the saturated zone) and included a brief update on thermal testing. The June 1998 meeting in Las Vegas will cover cross-cutting issues, a variety of updates, and any other topics that the Board wants to address in more detail for the VA.

A. Design

In the Board's view, there were several major accomplishments in the design area of the Yucca Mountain project in 1997. They include refinement of the designs for the repository surface and underground facilities and for the waste package; further integration of spent fuel owned by the DOE into disposal plans; continuing studies of criticality-control issues; and improved integration of engineering and performance assessment.

There also were a few shortcomings in the design area in 1997. There are continuing needs to adopt a more robust engineered barrier system and thoroughly explore different integrated repository and waste package designs that may offer the promise of better performance, lower cost, reduced uncertainty, or simpler operations.

The Board's findings, conclusions, and recommendations in the design area are presented below.

1. Repository Surface Facilities

The principal repository surface facilities would be on an 80-acre site at the repository's north portal and would consist of more than 15 structures and a small railyard. The functions of the north portal facilities would be to receive waste (principally by rail, but provisions would be made to receive some by truck) and package it for disposal. Except for the final closure welds and inspections of the waste packages, the Board considers all of the technology of the repository surface facilities commercially demonstrated and available. The estimated cost of the surface facilities is $3.9 billion.[1]

The design basis for the repository surface facilities assumes peak annual emplacement rates of 380 commercial spent-fuel waste packages, 100 glass waste packages, and 70 DOE-owned spent-fuel waste packages.[2] Depending on the waste characteristics, these emplacement rates are equivalent to specifying that the surface facilities be capable of processing waste at a rate of more than 4,500 metric tons per year. Considering that the maximum *average* emplacement rate will be approximately 3,300 metric tons per year, a rate of 4,500 metric tons seems too high. The DOE should reexamine the design basis to determine whether it is too conservative (i.e., whether the assumed peak annual emplacement rates in the design basis are too high).

The repository surface facilities include both dry-handling facilities (hot cells) and wet-handling facilities (pools). Much of the cost of the repository surface facilities is associated with the pools, where spent-fuel assemblies would be transferred from shipping containers to waste packages. Functionally, these pools duplicate what utilities already are capable of doing in their own pools, although some utilities are not capable of handling very large waste packages. If enough utilities package their spent fuel so that the services needed at the repository surface facilities are minimal, there could be savings in both the capital and the operating costs of the repository surface facilities. Whether additional preparation at the utilities for disposal would result in savings for the overall waste management system merits study.

For safety, standardization, and other reasons, the Board long has been in favor of examining concepts that reduce the amount of handling and transfer of spent-fuel assemblies within the waste management system.[3] One way of accomplishing this is to maximize the amount of preparation for disposal at the location where the waste was generated. A true multipurpose canister (MPC) concept is an example of a method that moves a substantial amount of disposal-preparation activity to the source of the waste. Other concepts also are worthy of study (e.g., multipurpose casks).[4] The DOE should reopen studies of these concepts. The DOE should ensure that the studies treat the entire waste management system as a single integrated system and that the examined concepts are fully capable of including all three functions of a waste management system: storage, transportation, and disposal.

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1. Presentation by M. G. Brodsky at the Board's meeting in Las Vegas on June 26, 1997 (NWTRB 1997b). According to Mr. Brodsky, life-cycle costs (construction, operating, and closure costs) for the repository surface facilities at Yucca Mountain would be $3.9 billion; for the repository underground facilities, $3.7 billion; and for the waste packages, $4.5 billion. All costs are in fiscal year 1997 dollars. The cost of any new rail system for bringing waste to Yucca Mountain is not included in these figures.
2. Presentation by P. G. Harrington on October 22, 1997 (NWTRB 1997c).
3. See, for example, the Board's 1993 summary report (NWTRB 1994).
4. As used here, a canister has thin walls—say, less than a few cm in thickness, and a cask has thick walls—say, 10 or more cm in thickness. A true MPC concept is one that uses the same canister for all three functions of a waste management system: storage, transport, and disposal. Similarly, a true multipurpose cask concept would use the same cask for storage, transport, and disposal.

2. Repository Underground Facilities

A plan view of the conceptual repository layout is shown in Figure 1. All underground drifts would have circular cross sections. The diameters of the ramps from the surface to the repository, the main drifts around the periphery of the repository, and the exhaust drift (which would be located approximately 10 m underneath the repository) would be 7.6 m, and the diameters of the emplacement drifts would be 5.5 m. The ramps and most of the east main drift exist now as the recently completed ESF. The balance of the main drifts and the exhaust drift would be constructed next, followed by emplacement drifts, starting from the north.

Waste would be emplaced in the drifts one at a time, starting with the northernmost emplacement drift and moving to the next drift south after a drift is filled. After an emplacement drift is filled, it would be closed off with doors at each end (where the drift intersects the main drifts on the east and west sides of the repository), limiting ventilation to insignificant amounts. Human entry into a drift would be prohibited after the first waste package has been emplaced in that drift. (Therefore, all operation, maintenance, inspection, testing, etc., in drifts containing waste would be done remotely.)

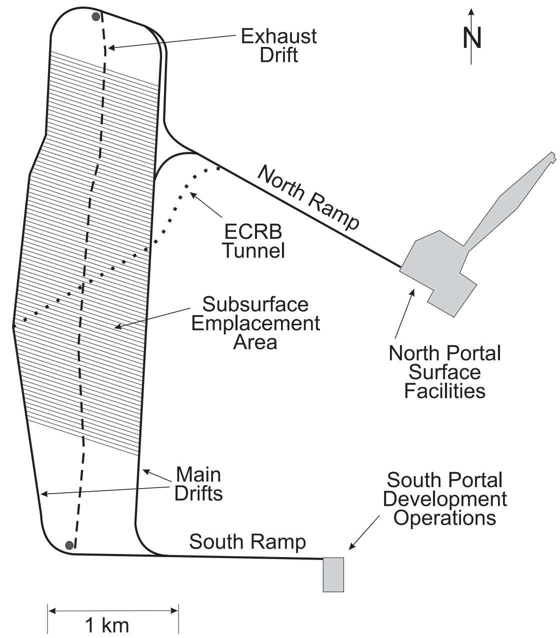
The Board has had, and continues to have, questions about this design, such as the following examples:

- **Why should the diameters of the emplacement drifts be 5.5 m?** Smaller-diameter emplacement drifts would be more stable and less expensive to construct and maintain, could eliminate the need for steel supports or concrete liners in much of the drifts and reduce the need elsewhere, and could give at least equal, if not better, long-term performance.

- **Has the potential effect of the exhaust drift underneath the repository on the long-term performance of the repository been evaluated?**

- **Is the value added by the exhaust drift worth its cost and potential effects, if any, on long-term performance?** The exhaust drift is not designed to allow more air to flow into or out of the repository than would be possible if the exhaust drift were not present; it simply allows the air to follow a different path.

Figure 1. Plan View of Conceptual Repository Layout



Source: Adapted from Harrington presentation at Oct. 22, 1997, Nuclear Waste Technical Review Board meeting.

- **Have the DOE's plans provided for the funds and time that will be needed to develop, demonstrate, and license the equipment, sensors, communication devices, etc., required for remote operations?**

- **Why are the benefits of continuous ventilation of all drifts not being taken advantage of in the current design?** Ventilation removes heat, reducing the maximum temperatures in a repository. Ventilation also removes water.

The Board is very interested in seeing serious study of alternative repository designs. Such designs must treat the entire repository as an integrated system. Examples of design concepts that could be explored include the following, individually and in combinations: (1) a design in which the maximum temperature of the rock midway between emplacement drifts never exceeds the boiling point of water (thus improving the likelihood of drainage between drifts of not only the regional percolation flux but also the reflux of water that might have boiled away from rock near the emplacement drifts); (2) a design that would *never* (not even in so-called "off-normal" conditions) need human entry into an emplacement drift containing one or more waste packages—in other words, a true totally remote operation; (3) conversely, a design permitting humans wearing typical work clothing to safely enter emplacement drifts containing waste packages to inspect, maintain, retrieve, or emplace them; (4) a design with a smaller emplacement-drift diameter (e.g., 3.5 m) and consequently simpler ground support; and (5) a design using preclosure or postclosure ventilation or both. The Board believes that these design concepts can be developed in a way that allows meeting all thermal constraints while retaining the current design's capability to dispose of 70,000 metric tons of high-level waste and spent fuel within the current repository footprint.

We realize that these ideas—and many others—are not new to the project. To the best of the Board's knowledge, however, none of them has received the kind of thorough, reasoned, integrated, and objective evaluation it deserves.

Although it is neither necessary nor appropriate that the alternatives be developed as fully as the reference design at the time the VA is delivered, we believe that including alternative design concepts in the VA could enhance the VA's value and credibility significantly. Thus, we urge the DOE to consider including alternative design concepts in the VA.

The Board is aware that the DOE has established and staffed an activity for identifying alternative design concepts. This activity is important for the integrity of the design process and should be continued. The Board believes that alternative design concepts can be identified, developed, and included in the VA without delaying the VA. In any case, starting this work should not be deferred, regardless of whether it can be included in the VA.

3. Engineered Barrier System (Waste Package)

The reference waste package design is a double-shelled cylinder nearly 2 m in outside diameter by 5 m long with a 2-centimeter (cm)-thick inner shell of corrosion-resistant alloy C-22[5] and a 10-cm-thick outer shell of carbon steel, a corrosion-allowance material. The waste package will be emplaced horizontally on pedestals in the emplacement drift.

Data obtained from the ESF within the last 2 years clearly show that the repository will be wetter than thought as recently as 3 years ago. This discovery has triggered examination of enhancements to the existing design.[6] Examples of such enhancements are drip shields and backfill. The Board is particularly interested in seeing studies of two design enhancements: (1) smaller waste packages and (2) a waste package design using two corrosion-resistant materials (CRM) rather than one CRM and one corrosion-allowance material, as in the present design.

Smaller packages could reduce peak temperatures and allow smaller drift diameters, and dual-CRM packages would be more robust. In other words, they would last longer (probably far longer) than the current design. For the existing waste package design, examining the question of whether the corrosion-allowance material would be better suited as the inner shell in a warm, moist repository would be worthwhile. This could prevent possible deleterious effects that carbon-steel corrosion products might have on alloy C-22.

5. Alloy C-22, a nickel alloy, replaced alloy 625, another nickel alloy, in late 1997 because alloy C-22 is even more corrosion resistant than alloy 625.
6. Enhancements are features that are added to or changed in a design without altering the fundamental nature of the design. In contrast, alternative repository designs are ones in which one or more fundamental design aspects are changed. The demarcation between design enhancements and alternative repository designs is not sharp.

The DOE is actively identifying and evaluating enhancements to the reference design.[7] We recommend that the descriptions and approximate costs of enhancements be included in the VA and that their effects on long-term repository performance be included in TSPA-VA sensitivity studies.

Although integration of performance assessment and engineering groups in the project has improved significantly, presentations at the Board's October 1997 meeting indicated that the two groups are not using the same approach for galvanic protection.[8] Specifically, it seemed that (1) the performance assessment group intends to give little or no performance credit for galvanic protection in its VA base case while (2) the engineering designers assume that the reference waste package design for the VA base case would provide galvanic protection.

Recently, the Waste Package Degradation Expert Elicitation (WPDEE) panel, the TSPA peer review panel, and the Yucca Mountain Site Characterization Project Mined Geologic Disposal System Consulting Board (all three groups are discussed later in this report) expressed opinions that galvanic protection is likely to provide no more than several hundred years of additional protection. It is highly unlikely that data obtained between now and the VA delivery date will refute, or confirm, these opinions with any degree of confidence.

Therefore, the Board believes that a prudent course of action for the VA reference design is to omit galvanic protection entirely or to rely on it for no more than a few hundred years. At the same time, the Board realizes that galvanic protection may have applicability and encourages continued experimental work in the area and sensitivity studies in VA cases other than the base case.

The Board agrees with information presented at its October 1997 meeting that shrinkfitting[9] is technically feasible and that it is not an expensive operation in itself. Unless the parts to be mated are machined with a high degree of precision, however, the residual stresses from the shrinkfitting will be variable. Concerns have been expressed[10] that the residual stresses left from shrinkfitting could exacerbate waste package corrosion or cause other unknown stress-related problems. The Board's understanding is that the principal (perhaps sole) justification for shrinkfitting is to promote galvanic protection. Because the additional performance that galvanic protection will provide may be limited, we question the wisdom of incorporating shrinkfitting in the VA.

In addition, the Board long has been concerned, as have scientists and engineers within the program, about the ability to perform inspections of the final closure welds (the welds made after waste has been placed in the package) of both the inner and the outer shells. We believe that this issue is completely resolvable and that its resolution may be postponed reasonably to well beyond the delivery of the VA. However, we point out that the current design makes the final closure welds, particularly those of the inner shells, difficult to inspect. Inspection needs and the broader issue of quality control in manufacturing will become important issues as waste package designs mature. Designers must be aware of these issues, even at the conceptual design stage.

7. See the DOE's responses to the design recommendations made by the Board in its 1996 summary report (NWTRB 1997a). The responses to the design recommendations are in Appendix D of this current report.
8. Galvanic protection can occur when two dissimilar metals are in contact with each other and with a saline solution. If oxygen also is present, the more reactive metal may corrode (oxidize) preferentially, thus "protecting" the less reactive metal by delaying the onset of its corrosion until the more reactive metal has corroded completely. Carbon steel is somewhat more reactive than alloy C-22 at temperatures below the boiling point of water.
9. Shrinkfitting is a way to put the inner and outer shells of the waste package together so that they have a close fit. The empty outer shell (without lids) is heated to approximately 500°C and expands. The unheated empty inner shell (without lids) is inserted in the outer shell. As the outer shell cools, it contracts around the inner shell.
10. TSPA peer review second report (TSPA Panel 1997b) and WPDEE final report (WPDEE 1997).

B. Total System Performance Assessment

TSPA is the principal method of evaluating the ability of the proposed repository (engineered and natural components acting together) to contain and isolate waste. It is essentially a predictive-computational model of repository performance over time. As noted above, the DOE is charged with carrying out a performance assessment that emphasizes the *probable behavior* of the proposed repository.

The DOE has devoted significant and laudable effort to achieving the goal of developing a credible TSPA. The emphasis on probable behavior has resulted in a division of the TSPA-VA into a base-case calculation and a series of sensitivity tests. The base case concentrates on probable, or expected, performance. The sensitivity studies concentrate on "What if?" scenarios for alternative input parameters and design features and for disruptive events, such as volcanic activity and earthquakes.

Two series of extensive workshops have increased interaction within the program and have given the DOE substantial expert input from outside the program. In one series, nine abstraction[11] and testing workshops were held in 1997. The workshops brought together field and laboratory scientists, conceptual modelers, and performance-assessment analysts from within the program on a series of important topics. Topics covered in the workshops included flow in the unsaturated zone, thermal hydrology, near-field geochemical environment, degradation of the waste package, degradation and mobilization of the waste form, transport in the unsaturated zone, flow and transport in the saturated zone, the biosphere, and criticality. The workshops have proven generally very successful.

The second series of workshops involved eliciting expert judgment, primarily from outside the Yucca Mountain project, for better defining the conceptual and parameter uncertainty of the important elements that go into the TSPA. This effort also has been successful and is discussed more extensively below and in Chapter 3.

The DOE also formed an external TSPA peer review panel in 1997 to delve into the important concepts and details of the TSPA-VA. It consists of six scientists and engineers who are experts in different technical fields.[12] The panel began meeting in early 1997 and made plans to issue three interim reports before the final publication of the TSPA-VA. The reports are designed to provide the DOE with critical reviews and comments that can help improve the quality of the TSPA-VA. After the TSPA-VA is published, the panel will issue its final review, along with suggestions on how to improve performance assessment for future iterations. The TSPA peer review panel issued two interim reports in 1997. They are discussed below.

The first interim report (TSPA Panel 1997a) aims at giving the DOE the panel's initial impressions and is critical of much of the TSPA effort. Although the panel acknowledges that its report is based on limited information, it found the TSPA effort lacking in several respects, including a clear overall conceptual model of repository performance, data on waste package performance, and conceptual models of waste form degradation. For example, the panel found inadequate justification of assumptions about the efficacy of galvanic protection of the inner waste package, ceramic drip shields, microbially influenced corrosion, and radionuclide transport. The panel also felt that overly conservative assumptions were being used about several phenomena.

The second interim report (TSPA Panel 1997b) provides comments on TSPA methodology and on several technical issues. In the report, the panel downplays the TSPA as being a rigorous predictive tool, preferring to think of it as a means of demonstrating a "reasonable expectation" of compliance with safety requirements. The report points out that

11. "Abstraction" is the term used by the DOE to denote the process by which highly complex models are replaced by simplified models to obtain computational efficiency.

12. The TSPA peer review panel is chaired by Dr. Chris Whipple (ICF Kaiser Engineers). Other members are Dr. Robert Budnitz (Future Resources Associates, Inc.), Dr. Rodney Ewing (University of Michigan), Dr. Dade Moeller (Dade Moeller and Associates, Inc.), Dr. Joe Payer (Case Western Reserve University), and Dr. Paul Witherspoon (Witherspoon, Inc.)

unrealistic bounding analyses can be misleading and presents concerns about the possible misuse of expert judgment as a substitute for data. The panel urges the DOE to increase its effort in model testing and to articulate a safety case for the proposed repository, integrating the results of TSPA and paying specific attention to defense-in-depth. Specific criticisms of several models are presented, particularly those related to hydrothermal processes, corrosion, water chemistry, glass-waste degradation, and transport of waste from the engineered barrier system.

The Board is encouraged by the strong and independent comments being provided by the TSPA peer review panel, many of which echo comments of the Board. The Board supports the DOE's continuing effort to pay careful attention to the panel's comments. We look forward to future reports.

C. Plan and Cost Estimate for License Application

A plan and a cost estimate for a license application constitute the third element of the VA. The Board will focus its review on the plans for and estimated costs of technical activities supporting a license application. In particular, the Board believes that data from the new enhanced characterization of the repository block (ECRB) program are vital for the Secretary of Energy's decision on the suitability of Yucca Mountain. This decision precedes submittal of a license application to the U.S. Nuclear Regulatory Commission (NRC). Many other vital ongoing technical activities (such as the long-term corrosion test program, the drift-scale thermal tests, and hydrologic and geochemical tests in wells and in the ESF) must continue to support licensing, and the Board wants to ensure that these activities are included in license application plans and cost estimates.

D. Repository Cost Estimate

This is the fourth (and final) element of the VA. Because the Board's purview is technical, the review will be confined largely to the aspects of the cost estimate that involve technology development. For example, the Board is particularly interested in techniques, allowances, and contingencies used in the cost estimate to reflect the costs of technology development (e.g., manufacture of prototypical waste packages, development and testing of robotic or remote handling systems for remote emplacement and monitoring) and to reflect current technical or engineering uncertainties. Another cost issue that the Board will explore is how potential enhancements to the repository design that are not part of the reference design case are handled.

The Board was pleased to learn at its October meeting that an independent review of the cost estimate for the mined geologic disposal system will be performed for the VA by a major U.S. engineering-construction firm. It is important that the DOE clearly define for the cost-estimate reviewer the construction process and the contracting basis (e.g., fixed price, cost plus) that will be used to construct the repository.

E. Recommendation

The Board views the DOE's work on alternatives to the reference design as a vital element in the repository program. Although much of this work will be carried out subsequent to the VA, the DOE should consider including, in the VA, cost estimates of alternative repository design concepts and sensitivity studies showing the effects of these alternative design concepts on long-term repository performance. Work on alternative repository designs should be started now, even if it cannot be included in the VA.

II. Regulations, Standards, and the Environmental Impact Statement

The Nuclear Waste Policy Amendments Act of 1987 (NWPAA 1987) calls for three sets of regulatory requirements for a geologic repository. The regulations are to be developed by three federal agencies. The DOE is to develop guidelines for selecting repository sites, the U.S. Environmental Protection Agency (EPA) is to promulgate environmental radiation protection standards for repositories, and the NRC is to develop technical requirements for licensing repositories. We comment below on the first two sets of regulatory requirements.

The NWPAA also calls for the development of an environmental impact statement (EIS) for a repository at Yucca Mountain. The DOE's work on the EIS in 1997 and the Board's outlook for the EIS in 1998 are discussed briefly below.

A. Siting Guidelines

In a letter to the DOE on April 15, 1997, the Board submitted comments (Cohon 1997b) on the DOE's draft revisions (USDOE 1996) of the DOE's repository siting guidelines, 10 CFR 960. In the draft revisions, the determination of whether the Yucca Mountain site is suitable for developing a repository would depend no longer on several individual criteria. Instead, a suitability determination would be based solely on whether the repository system (natural and engineered barriers) can meet a post-closure risk-based standard that will be specified by the EPA. In the draft revisions, the DOE proposed using the TSPA methodology to support this determination. In effect, the former multiple criteria would be integrated and subsumed into a single performance standard.

The Board's April 15 letter indicated that the proposed revisions represent a step in the right direction. It expressed concern, however, that the revised guidelines might be perceived as "changing the rules in the middle of the game," increasing the fears of some that performance assessment may be manipulated to support any conclusion desired. For that reason, the Board laid out the following five areas for strengthening the proposed revisions.

1. **The DOE should show in its performance assessments that the repository system is designed in a way that preserves the principle of defense-in-depth using multiple barriers.** The Board strongly believes that the principle of defense-in-depth using multiple natural and engineered barriers must be preserved in any strategy for waste containment and isolation. The Board would object strongly if the revised guidelines were to have the effect of diluting the DOE's commitment to that principle. The Board does not, however, want to prescribe a particular mix of barriers that the DOE must adopt. Thus, in the Board's view, a site may be suitable even if the repository system has to rely on engineered barriers to a greater degree than was envisioned when the current guidelines were published.

2. **The DOE should add a requirement that performance assessment not only shows that the repository system complies with a standard but also shows that it does so robustly**. A performance assessment conclusion is more likely to be accepted as robust if (a) uncertainties are fully and accurately addressed, (b) sensitivity studies are carried out to show the effects of different assumptions on variables, and (c) compliance is shown with a margin of safety.

3. **The DOE should specify the level of confidence that must be reached in its performance calculations before it makes a site-suitability determination**. Because the results of the TSPA may involve substantial uncertainty, it is essential that the DOE specify in advance the level of confidence needed to make a positive site-suitability determination. That level should be expressed quantitatively whenever possible, although only a qualitative definition may be feasible in some areas. This acceptable level of uncertainty is, of course, a policy judgment that is clearly the DOE's to make. The Board believes, however, that the credibility of the process will be increased if interested parties besides the DOE and its contractors are involved in making that call. The DOE should provide sufficient explanation for whatever level it decides on so that those affected have a clear understanding from the start about how the DOE will use the performance assessment's conclusions to make decisions.

4. **The DOE should add a requirement that performance assessment be carried out in a way that is highly transparent to the technical community, regulators, and interested members of the general public**. By "transparent," the Board means the ease of understanding (a) the process used to carry out the TSPA, (b) the assumptions that drive the conclusions, and (c) the rigor of the analyses that lead to the conclusions. A performance assessment is likely to be more transparent under the following conditions:

- Assumptions and methodologies used in the analyses are identified clearly and explicitly, the bases for them are explained clearly, and their effects on the assessment's conclusions are presented clearly.

- Key parameters and their distributions can be traced back to specific experiments and investigations or to formal or informal expert judgments.

- The TSPA has undergone independent and comprehensive outside review.

5. **The DOE should formally connect its site-suitability determination to a larger and public process for making the decision on whether to recommend to the President that Yucca Mountain be developed as a repository.** Without such a process, developing a broad national consensus that Yucca Mountain is "safe enough" will be difficult. Although performance is a central consideration in the evaluation of a repository system, additional considerations need to be assessed and appropriately weighed. The additional considerations include cost, environmental impact, socioeconomic effects, and transportation risks.

B. The DOE's Interim Performance Measure

In the absence of environmental standards from the EPA, the DOE has developed an interim performance measure. The interim performance measure is for the DOE's own use in guiding its technical program and communicating with others about the potential performance of a repository at Yucca Mountain. The interim performance measure will be discarded if the EPA (or the NRC) sets standards, or the equivalent, for a repository at Yucca Mountain. In developing the interim performance measure, the DOE took into account the 1995 report of the National Research Council's Committee on Technical Bases for Yucca Mountain Standards (National Research Council 1995). The interim performance measure has the following major features and assumptions.

- The interim performance measure is the expected annual dose to an average individual in a critical group living 20 km from the repository.[13]

- Estimated doses shall not exceed 25 millirems (mrem) per year for 10,000 years, and that numerical value will become a "goal" thereafter.

- The consumption of food and liquids by the critical group is to be defined on the basis of surveys of today's dietary patterns near Yucca Mountain. The critical group is composed solely of adults.

- The performance measure applies to the combined dose from all pathways, including ingestion of drinking water, consumption of food, and direct exposure. Therefore, the DOE sees no need for a separate standard for groundwater protection.

- The estimated doses will include contributions from undisturbed repository performance and from releases from the repository caused by natural disruptive events. Disturbance by human intrusion will not be included. Instead, the DOE will evaluate human-initiated disturbances separately, as recommended by the National Research Council.

For evaluating compliance with the DOE's interim performance measure, a biosphere model is needed that can predict how radionuclides released to the environment will pass through food chains and other pathways leading to radiation doses to humans. The DOE will use an existing computer code to project doses and will use mostly generic data except for some information from the Nevada Test Site and the dietary information developed from surveys of people now living near Yucca Mountain. Because the rate of precipitation might affect the biosphere model's results (e.g., increased rainfall might marginally decrease needs for irrigation well water), three rates of precipitation (one, two, and three times today's rate) will be evaluated as bounds on future climate conditions. Chapter 2 presents a more detailed discussion of biosphere modeling for a Yucca Mountain repository.

13. Farms in Amargosa Valley are about 30 km from the repository, so the assumption of a location of the critical group 20 km from Yucca Mountain would introduce some conservatism into an analysis. That is, it would result in a *higher* dose.

C. Conclusion

With one exception, the DOE's interim performance measure seems appropriate for DOE's use. The exception is the DOE's exclusion of children from the definition of the critical group.

D. Recommendation

The DOE should estimate *and disclose* the likely variation in doses for alternative candidate critical groups characterized by different locations, ages, and lifestyles. In particular, potential doses to children should be compared with doses to adults within each candidate critical group.

E. Environmental Impact Statement

If the site is determined to be suitable, the DOE's plans are for the Secretary of Energy to recommend to the President in 2001 that the President approve Yucca Mountain as a site for a repository. According to the NWPAA, the Secretary's recommendation must be accompanied by an EIS.

Much of the work on the EIS was deferred in 1996 in response to reduced appropriations for fiscal year 1996. In 1997, the DOE resumed work on the EIS in earnest. The DOE's EIS contractor, selected in 1996, mobilized staff, familiarized them with the project, and began to assemble and analyze data for the EIS. In 1998, the Board will be devoting some of its time to understanding the organization and content of the EIS. In particular, the Board believes that selecting and developing alternatives, including characterizing the "no action" alternative, is critical to the technical success of the EIS process. The Board strongly endorses development of alternative repository and waste package designs and believes that the EIS process is an appropriate forum for exploring these alternatives.

III. Transportation

A. Introduction

The Board's Panel on the Waste Management System held a meeting on November 19 and 20, 1997, in Arlington, Virginia. Safety in transportation of spent fuel, the focus of the meeting, has been the subject of many Board and panel meetings over the years. This meeting dealt with safety as it applies generally to spent-fuel transportation without concentrating on any specific program, including the DOE program. The Board has been briefed in the past on the DOE's market-driven approach to acquiring transportation services and will continue receiving updates in the future.

B. Discussion

The meeting dealt with three topics. The first was federal regulations governing the transportation of spent fuel. The regulatory responsibilities are divided between the U.S. Department of Transportation (DOT) and the NRC. The DOT covers most aspects of transport operations, such as carrier qualifications and placards, shipping papers and other communication requirements, and safety regulations that apply generally to all freight carriers regardless of the nature of the cargo. The DOT also is responsible for highway routing regulations, although it has not promulgated analogous requirements for rail routing. The NRC's major responsibility is in certifying the design of the transportation cask, a massive metal container that provides shielding protection while the spent fuel is in transit and protection against breach and release in an accident. The NRC also has the responsibility for safeguards and physical protection, measures that address theft and sabotage. Both agencies have inspection and enforcement programs for ensuring compliance with their regulations.

The second topic of the meeting was analyses of risks associated with transporting spent fuel. The analyses included data on the historical safety performance of many past shipments and analyses and tools intended for predicting the risks of prospective shipments. The analyses and tools were developed in the past under the sponsorship of the DOE and the NRC and have been used in statements in both agencies' environmental assessments. The panel chose to review this subject because of the prominent use of these analyses and tools in assessments of the safety and health risks of future shipments. It must be noted, however, that these tools are not without controversy and have their critics.

Spent fuel has been transported for nearly four decades. An NRC document (NRC 1997) shows that the total number of shipments overseen by the NRC from 1979 to 1996 in the United States was 1,319 (1,172 by highway and 147 by rail). Not included in the 1,319 figure are 684 shipments of spent naval fuel since 1957, several shipments of research-reactor spent fuel, and some shipments of DOE-owned spent fuel.[14]

No transportation accident resulting in a release has been recorded since the DOT began keeping records in 1971. Quantitative analyses about cask performance under accident conditions (specifically, the so-called "Modal Study"[NRC 1987]) predict very low probabilities of release. These analyses and risk analysis tools, such as RADTRAN, are accepted by federal agencies for assessing transportation risks. The tools also have their critics. Examples of shortcomings cited by critics include assumptions about cask capacity (new-generation casks will have much larger capacities) and the role that human error may play in manufacturing, quality control, and operations.

The third topic of the meeting was transportation practices and experiences. There were presentations about the transportation of both commercial spent fuel and Navy spent fuel. The Naval Propulsion Program has had considerable experience in transportation of spent fuel. Under the program, spent fuel has been transported from a small set of seaports to the same destination (Idaho National Environmental and Engineering Laboratory), using the Navy's own rail casks and cars.

Experience in transporting commercial spent fuel, although spanning a similarly long period, does not have the same kind of continuity. The origins and destinations, as well as other important parameters (such as transport modes and routes), change from one shipping campaign to another. Thus, the presentation on transporting commercial spent fuel using, as an example, the experience of moving all of the spent fuel from the closed Shoreham plant on Long Island, New York, to the Limerick plant in Pennsylvania, may be more indicative of the planning and implementation challenges that will have to be faced when the spent fuel now stored at the various utility sites will have to be shipped.

The existing fleet of casks for transporting spent commercial fuel is small in both number and individual capacity. Most of the casks in the existing fleet cannot be replicated because their designs do not meet current NRC regulations. If large quantities of spent fuel are to be shipped, new-generation casks with much larger capacities, some of which are before the NRC now for certification, will have to be made available. In addition to development of the physical capacity to carry the fuel in larger quantities than in the past, there are myriad logistics, planning, and coordination issues that must be resolved. Routing, coordination with state and local governments along the various routes, and other institutional issues are among the pretransport activities that must be undertaken.

In the roundtable discussions that followed the formal presentations, several issues surfaced. In addition to those already noted, some of the more recurrent ones were the following:

- **Full-scale testing of transportation casks.** The NRC does not require full-scale testing to demonstrate that a cask design complies with the NRC's regulations about cask performance under severe accident conditions.

- **Use of dedicated trains for rail transportation.** Existing federal regulations permit rail transportation of spent fuel in trains used in ordinary commerce—that is, trains containing a mix of freight cars. There are perceived advantages in using dedicated trains for both safety and logistics management. The Hazardous Materials Transportation Uniform Safety Act of 1990 (U.S. Congress 1990) required the DOT to perform a study of the use of dedicated trains for spent fuel. The study has not been released.

14. Presentation by R.A. Guida on November 19, 1997 (NWTRB 1997d).

- **Reexamination of the NRC's transportation environmental statement.** The NRC's *Final Environmental Statement on The Transportation of Radioactive Material by Air and Other Modes*, commonly referred to as "NUREG-0170," was published in 1977 (NRC 1977). It needs to be reexamined and updated as necessary.

C. Conclusions

1. **The Board continues to believe that the risks associated with transporting spent fuel are low**. The Board also believes that these risks can and must be kept low for future transportation. Although historical safety performance has been good, future transportation of spent fuel from the various reactor sites throughout the country to a centralized facility—a repository or an interim storage facility—represents a large increase in both scale and operational complexity in comparison to past shipments. There may be more opportunities for mishaps and human error in construction and operation. For maintaining a good safety record, a heightened safety program may be needed in the civilian nuclear waste management program.

2. **The existing capability to transport spent fuel is small, and much preparatory work needs to be done before fuel can be transported in large quantities.** At least several years of preparatory work will be necessary for spent fuel to be transported in large quantities. New-generation casks with large capacities will have to become available. Infrastructure and access at the destination and, perhaps, at some of the originating sites will have to be developed. Many institutional issues of concern to state and tribal governments—for example, routing and emergency response—will need to be addressed. Resolving these institutional issues may require as much time as, or perhaps more time than, developing the physical infrastructure.

3. **Other decisions, such as use of dedicated trains and full-scale testing of casks, may enhance the perceived level of safety.** To what extent these measures would add to overall transportation safety is unclear, but they may increase confidence in the safety performance of the transportation system. Therefore, they are options that could be considered by policy makers.

IV. What Happens When Radioactive Waste Reaches the Water Table?

Any water that flows through the repository may eventually flow through the unsaturated zone below the repository and into the saturated zone. There, it will commingle with groundwater slowly moving toward natural discharge points some 30 to 50 km to the south.

Estimates of the concentrations of radioactive materials entering the environment south of a Yucca Mountain repository will be highly uncertain. The saturated zone is highly fractured and faulted, causing groundwater flow to be channeled within the more transmissive zones of fractured rock. Within these zones, groundwater movement will be faster than the average groundwater flow rate through the saturated zone, and retardation of radionuclides may be less than average. Mixing of groundwater containing radionuclides and radionuclide-free groundwater within the saturated zone will dilute radionuclide concentrations, but demonstrating the degree to which mixing would occur in a channeled flow system may prove very difficult.

Perhaps a greater source of dilution may be mixing at a wellhead when groundwater is withdrawn from an aquifer into the biosphere. This depends on the specifics of the well withdrawal. Dilution by flow and transport in the saturated zone is difficult to quantify, at least in part because of the data limits.

The fate of radionuclides after they enter the biosphere and as they enter food chains and potentially cause radiation doses to humans must be projected. Using generic data in models of the transfer of radionuclides through food chains may cause large uncertainties in estimated radiation doses, perhaps as much as three or four orders of magnitude (a factor of 1,000 to 10,000).

Chapter 2 contains a more detailed discussion of the fate of radionuclides after they reach the water table.

V. Construction at the Site and Scientific Developments

A. Completion of the Exploratory Studies Facility

The excavation of the ESF was officially completed on April 25, 1997, providing a 7,877-m-long tunnel at Yucca Mountain. The excavation of this tunnel provided a wealth of anticipated and unanticipated data on the geologic and hydrogeologic character of Yucca Mountain. The excavation also was a very valuable learning opportunity for the Yucca Mountain project in performing contractor oversight, managing construction, and understanding the value of seeking independent counsel from construction industry experts. A brief description of the tunnel excavation is presented below, followed by a brief discussion of the more prominent lessons that can be learned from the construction of the ESF.

1. The Tunnel

The 7.6-m-diameter ESF tunnel loops downward from the north portal to the repository horizon, continues along the eastern edge of the repository block, and then loops upward to the south portal. Approximately one quarter of the tunnel length required structural steel supports, and the remaining length was reinforced by installing about 32,000 rock bolts. Tunnel construction produced approximately 700,000 cubic meters of excavated rock. Construction was started officially in October 1994 and was completed approximately 31 months later. The excavation was conducted over a period having 640 work days available, for a net production of about 12.3 m per day.

2. Observations Derived from ESF Engineering and Construction

The ESF was designed as a conventional underground excavation. The construction experience can be viewed as a learning opportunity for planning and constructing the repository. The Board makes the following observations:

Industry expertise is important and accessible. In 1995, after experiencing severe difficulties in the excavation of the ESF, the DOE, in conjunction with the management and operating contractor (M&O), established a consulting board. As described in our 1996 summary report (NWTRB 1997a), the consulting board has been very effective in achieving improvements in the repository design and in the proposed construction sequence. Recently, the consulting board was renamed[15] and restructured to include two subboards. One subboard provides guidance on subsurface repository design and construction, and the other provides guidance on the design and fabrication of the waste package, waste package materials, and the design of the repository surface facilities.

The DOE and the M&O are commended for involving expert consultants, a practice long used in industry. The Board notes that the impressive qualifications of the members of the consulting board indicate that there are additional opportunities for involving them as consultants on program management rather than only as technical advisors for evaluating designs.

Tunnel diameter has a significant effect on construction difficulty in the site rock units. The perspective of the DOE and the M&O has been that a large tunnel (7.6-m diameter) is required for the ESF and for all of the service tunnels (the main drift and the exhaust drift) yet to be built for the repository. The most frequent argument made by the DOE and the M&O in support of large tunnels is that the large diameter is needed for possible ventilation purposes. ESF experience in rock units at the site shows that construction of such large tunnels has a significant effect on cost and time of excavation and support. The Board encourages careful consideration of tunnel sizes needed for service tunnels and emplacement drifts. If consideration of integrated repository operation allows, diameters should be reduced wherever warranted.

15. Yucca Mountain Site Characterization Project Mined Geologic Disposal System Consulting Board.

Construction contract options are available for sharing risks. In cost-plus contracts, such as used by the DOE for the ESF, all risks are assumed by the owner (the DOE, in this case), and profit or fee is a matter of subjective judgment. Underground construction worldwide is implemented through competitive processes, normally involving fixed-price contracts, sometimes called "performance contracts." These contracts assign design, procurement, and disposal of construction equipment, including tunnel-boring machines, to the construction contractor. Performance contracts give the contractors incentive for using their experience and skills in addressing unanticipated risks to produce a profit. The very efficient, cost-effective underground construction managed by the DOE on the Superconducting Super Collider project was an excellent example of using performance contracts. Such contracts should be strongly considered by the DOE in contracting for future underground construction at Yucca Mountain.

In addition, as noted by a consulting board member who is a highly experienced expert in program management, construction costs cannot be estimated independently of the engineering and construction contracting process. The two are directly interdependent. Thus, to be credible, the VA cost estimates for constructing the repository must be accompanied by a description of the contracting and management process that will be used.

B. Enhanced Characterization of the Repository Block

The Board's recommendation (NWTRB 1997a) for an east-west exploratory tunnel envisioned a small-diameter 1,200-m-long east-west tunnel at the elevation of the repository and parallel to the proposed emplacement drifts. The principal focus of the east-west exploratory tunnel would be to obtain data for reducing the uncertainty of the hydrogeologic environment within the repository.

The DOE has accepted this recommendation in general but has expanded the scope to what is known as the "enhanced characterization of the repository block" (ECRB) program. Planning by the DOE for this effort started on March 17, 1997, and the plan was approved on August 20, 1997. The approved budget is $40.7 million and consists of $20.1 million for design and construction of a smaller tunnel, $16 million for scientific testing, and $4.6 million for two boreholes, which will be drilled from the surface. The DOE plans to complete all excavation, including three alcoves, by January 1, 1999. The approximate route of the ECRB tunnel is shown in Figure 1.

The tunnel will be 15 to 20 m above the crown of the repository waste-emplacement drifts and about 5 m in diameter. The tunnel will start from the north ramp and cross the block in a southwest traverse, ending on the west side of the Solitario Canyon fault at a length of 2,815 m. This orientation will permit observation of rock conditions at a different orientation than that seen in the ESF and will allow excavation through the full range of emplacement-drift rock units. Observed rock behavior will yield information needed for the DOE's decision on emplacement-drift orientation and on the performance of the emplacement-drift-size tunnel-boring machine excavating in rock very near the repository horizon.

The tunnel-boring machine is scheduled to start excavation operations by March 9, 1998, and will complete excavation to the west side of the Solitario Canyon fault by August 31, 1998. Three test alcoves then will be excavated along the tunnel for performing hydrogeologic testing. The first alcove will be located above a niche in the ESF main drift to allow percolation testing between the two levels. The second alcove will be located below the edge (i.e., termination) of the nonwelded layer of the Paintbrush Tuff formation (Ptn) overlying the proposed repository. This location is predicted to be a high-infiltration region below the crest of Yucca Mountain. The third alcove will be across the Solitario Canyon fault zone.

The Board supports the decision by the DOE to excavate the ECRB tunnel expeditiously. Although hydrogeologic testing may not start until 1999, observations, mapping, and limited data on chlorine-36 (^{36}Cl) may be available before the scheduled delivery date for the VA, thus providing valuable confirmatory data for the VA.

C. Thermal Testing at Yucca Mountain

One of the primary functions of the ESF is to provide access to the strata in which the repository is to be located to conduct thermal testing. Data from thermal testing will be useful for validating the various hypotheses and assumptions used in developing performance models and the current repository design. Two tests are being conducted in the ESF, the single-heater test and the drift-scale test. In addition, a heater test is being conducted on the surface near Yucca Mountain on an excavated outcrop of welded tuff. It is referred to as the "large-block test." These tests are described briefly below.

1. Single-Heater Test

The single-heater test (SHT) has been in its cool-down phase since May 1997, and the plan is to end all testing by the end of January 1998. After testing is complete, post-test analyses of the SHT block will be performed, including sampling and overcoring of SHT boreholes. Key elements of the SHT final report, including all information from pre-test characterization through post-test analyses, will be incorporated in the VA.

2. Large-Block Test

The large-block test (LBT) was designed to promote formation of reflux (heat-pipe) zones[16] by controlling the temperatures along a horizontal plane of heaters to about 140°C and maintaining the temperatures at the top of the block at 60°C. This will form a heat-pipe zone between the heaters and the top of the block. Water, mobilized as vapor, is expected to be driven out of the pores and to flow upward. A 1-m-thick zone at the top of the block will be below boiling temperature, allowing the water to condense. The condensate then will return as reflux to the above-boiling zone. The DOE plans to maintain this zone in a stable temperature field for at least 1 month. This period should be sufficient for rock-water interactions to occur that would allow evaluation of (1) fracture healing and secondary mineral formation, (2) conditions under which liquid moisture can enter the above-boiling zone, and (3) whether heat conduction will overwhelm the heat-pipe effects.

On February 28, 1997, the LBT heaters were turned on. Early test results indicate the following:

- The rock properties initially assumed from the Yucca Mountain site-characterization program appear to be inappropriate, resulting in predictions that temperatures would never exceed the boiling point (97°C). Preliminary test data show temperatures rising to around 140°C.
- The heat-pipe responses can be very quick, a matter of a few hours or less, with short-duration (transient or episodic) refluxing, and can be very dependent on the rate of drainage of fluid through the fractures.
- A significant dryout zone will develop around the heaters if the fracture permeability is sufficiently high and the heat is not lost.

3. Drift-Scale Test

The drift-scale test (DST) is an integral part of the DOE's thermal test strategy that encompasses laboratory tests through studies of large-scale natural analogues. After the 47.5-m-long test area was excavated, it was equipped with nine canister heaters approximately the size of potential waste packages. Fifty wing heaters were installed in horizontal boreholes radiating from the drift to simulate the heat that would come from adjoining drifts, and approximately 3,500 sensors were installed. The sensors are used to measure thermal, mechanical, hydrologic, and chemical responses in the rock.

On December 3, 1997, the heaters were turned on. The data from the sensors in the rock mass surrounding the drift will allow comparison of measurements and predictions. Such measurements and comparisons will be used to verify input properties

16. Refluxing (sometimes referred to as "heat pipes") occurs when vaporized water moves along fractures, away from the heat source, to cooler rock, where the vapor cools and condenses back to water, sometimes draining back to the heat source.

and process models and provide an understanding of the heating and subsequent cooling process. The heating phase is planned to last approximately 4 years, with nominally 4 years for cooling afterward.

The DOE is to be commended on implementing this extensive thermal test facility. The heater turn-on is the culmination of many months of effort by M&O and DOE staff to define the testing needs, integrate the competing demands of the investigators from the three national laboratories working on the DST, and excavate and instrument the facility, all well within, actually ahead of, schedule. The Board encourages the DOE to use the DST data expeditiously and continually update and refine analyses of repository performance. These analyses also should be used to prepare more-detailed plans for activities related to repository performance confirmation.

VI. The DOE's Use of Outside Experts

As noted earlier, the Yucca Mountain project is receiving valuable advice from two DOE-funded external review groups: the TSPA peer review panel and the Yucca Mountain Site Characterization Project Mined Geologic Disposal System Consulting Board. In the past, the Board has urged the DOE to make greater use of expertise outside of that already found within the Yucca Mountain project. The Board is pleased that the DOE is doing so.

In Chapter 3 of this report, another type of external input is described: recent specially elicited expert judgment. Expert judgment is required when dealing with an inherent uncertainty in scientific understanding or when there is a need to make an assessment before all relevant data can be collected. An example of the latter is the TSPA for the VA. Although informal implicit or explicit expert judgment from one or more Yucca Mountain scientists has always been used in performance assessment, the recent elicitations are formally structured studies that involve multiple experts, most of whom are from outside the Yucca Mountain project. The topics covered by the expert studies (some of which are not yet complete) include seismic and volcanic hazards, unsaturated zone flow, waste package degradation, saturated zone flow and transport, near-field / altered-zone coupled effects, and waste form degradation and radionuclide mobilization. A primary purpose has been to describe the uncertainties associated with particular models and data.

Overall, the elicitations have proven very successful. The DOE is commended for carrying out these studies and, in particular, for including a substantial number of outside scientists and engineers on the expert panels. Aside from supplying information that can be used directly for performance assessment and design, the elicitations have provided important insights into the program. They include the endorsement or rejection of previously accepted scientific models and design assumptions; the importance, or lack thereof, of different hypotheses; and the need to acquire selected additional data. The challenge to the DOE is to make full and effective use of the experts' input.

In making full and effective use of the expert elicitations, the DOE needs to articulate how it intends to aggregate the views of multiple experts and address the potential problems posed by receiving input on some issues from only a small number of the experts who were asked. This is especially important when there are relatively few experts and they differ sharply on significant issues. Sufficient information must be presented to trace the effect of an individual expert's judgment on overall conclusions. The DOE needs to explain whether and how the views of individual experts will be treated in sensitivity studies for the TSPA-VA, and it also should consider developing guidelines on how it will treat the results of an expert elicitation in the light of new data and analyses.

VII. Review of the Possibility of Hydrothermal Upwelling at Yucca Mountain

At the Board's January 1997 meeting in Pahrump, Nevada, Mr. Jerry Szymanski handed the Board summaries of 11 reports and articles based on recent studies funded by the Nevada Nuclear Waste Project Office. The documents argue that there is evidence of ongoing intermittent hydrothermal upwelling at Yucca Mountain and that the upwelling would render the site unsuitable for development as a repository. Subsequently, the Board received requests from both the Committee for the Truth About Yucca Mountain (Chrisman 1997) and the Attorney General of the State of Nevada (Del Papa 1997) to review this material.

Mr. Szymanski has raised questions previously about a possible future upwelling at Yucca Mountain. His previous work was reviewed thoroughly by outside experts, including a prestigious 17-member panel of the National Academy of Sciences (NAS). The panel's broadly based review was published in 1992 by the NAS in a report titled *Ground Water at Yucca Mountain—How High Can It Rise?* (National Research Council 1992). As stated in its sixth report (NWTRB 1992), the Board saw no reason to disagree with the panel's unanimous conclusion that "... from the geological features observed in the field and geochemical data, there is no evidence to support the assertion [by Mr. Szymanski] that the water table has risen periodically hundreds of meters from deep within the crust." The sixth report also noted that if significant new data or modifications are presented in the future, the Board will consider reviewing them at that time.

The Board has examined the material (in the form of reports) submitted by Mr. Szymanski and has concluded that some new information has been presented. The Board has decided to evaluate the quality and significance of this information. Three scientists[17] were contracted to assist the Board in its review, which we plan to conclude in 1998.

VIII. International Activities

A. Board Trip to Canada

A small group of Board members and staff visited representatives of Atomic Energy of Canada Limited's (AECL) Whiteshell Laboratories in Pinawa, Manitoba, Canada, on September 14-16, 1997. The purpose of the visit was (1) to receive an update on research conducted by the staff at Whiteshell Laboratories that is pertinent to the eventual disposal of high-level radioactive waste and (2) to visit the underground research laboratory (URL) before significant organizational changes still in process at AECL take place that could affect research and development work at Whiteshell Laboratories on high-level waste.[18]

Board members were briefed on research being conducted at Whiteshell Laboratories on buffers and concrete, the waste container, hot cells, the biosphere, siting and solute transport studies within fractured granitic rock, excavation and thermal response studies, and sealing studies. Board members were given a tour of the URL, including an update on experiments on radionuclide migration in a quarried block, solute transport in moderately fractured rock, and tunnel sealing.

As in its past visits, the Board continues to be impressed with the level of knowledge on the part of the AECL staff at Whiteshell about the technical issues involved in potentially disposing of high-level waste in the Canadian granitic shield. The research and development program has benefited from strong scientific and technical coordination and from development of scientifically based and reliable process models that are based on observable data. The program at Whiteshell Laboratories also has made considerable progress in identifying and

17. Dr. Robert J. Bodnar, C. C. Garvin Professor of Geochemistry at The Virginia Polytechnic Institute & State University; Dr. Patrick R. L. Browne, Director of the Geothermal Institute at the University of Auckland, New Zealand; and Dr. John W. Valley, Chairman of the Department of Geology and Geophysics at the University of Wisconsin, Madison.

18. For a more detailed description of the organizations involved and the Canadian approach to managing disposal of spent fuel, see NWTRB 1991, Appendix D. Although it is still unclear if and where research and development related to spent-fuel disposal will be conducted, organizational changes are in process that will affect AECL's role and possibly the roles of other organizations in Canada's high-level-waste program. Such decisions are still in process, however, and depend on negotiations under way among AECL, the government of Canada, and other entities.

characterizing fast pathways for groundwater flow (i.e., fracture zones and fault zones), as well as in conducting in situ and block experiments designed to obtain understanding of fractures and radionuclide migration and retardation. Water levels have been monitored in a network of wells that were constructed in advance of building the URL with that express purpose in mind. Research continues in the Canadian program to study backfill and shaft and tunnel seals, documentation of which will be important to any eventual assessment of a repository's performance.

To ensure that new experiments will not compromise ongoing work, managers and staff at Whiteshell Laboratories review all proposals for research to be conducted at the URL before the projects are approved. When geotechnical, hydrogeologic, geochemical, and model simulation uncertainties appear, site-specific experiments are designed and implemented by the staff at Whiteshell Laboratories to address the uncertainties.

B. Canadian Environmental Review

Board members were briefed by Dr. Kenneth W. Dormuth, director of the nuclear waste program at Whiteshell Laboratories, on issues raised during the extensive public hearing conducted by the Environmental Assessment Review Panel (EARP) under the auspices of Canada's Minister of the Environment. The EARP process began with the appointment of the panel in 1989. The EARP held open houses in five provinces and held numerous scoping meetings, appointed a Scientific Review Group (SRG) to perform a scientific evaluation of the disposal concept, and issued final guidance to the AECL, which in turn submitted its own EIS in September of 1994 (AECL 1994a and b). From November 1994 through March 1995, the EARP held open houses to explain the review process, which then took place in three phases from March 1996 to March 1997. Current estimates are that the EARP will issue its findings and recommendations to the government in the fall of 1998.

Some of the key issues raised during the public hearing process, as observed by those working at Whiteshell Laboratories, included the implications of deferring site selection, opposition to deep geologic disposal, use of a "case study" approach in developing safety-assessment models, potential effects on people near the disposal site and along the transportation routes, and site-specific questions about the design of a disposal facility (Dormuth 1998).

C. Similar Issues in Other Countries

Many of the issues raised during the almost 9-year EARP review process conducted throughout Canada are similar to the issues that have been raised over the years in other developed countries. Some of these issues are discussed below. The questions are raised as those charged with seeking scientific and technical solutions to the problems of nuclear waste disposal continue their work. Representatives of the public, citizen groups, environmental groups, the nuclear industry, politicians, and the research and development community grapple with questions that center on the ultimate safety of long-term geologic disposal. A socially acceptable decision based on sound science and technology has yet to be implemented.

In Switzerland, for example, underground exploration at the Wellenberg site, a potential location for the disposal of low-level and intermediate-level waste, has been slowed by a referendum initiated by the people living in the canton where the facility would be located. As a result, a phased approach to site selection has been initiated, and the issues of long-term monitoring and retrievability of the waste are being examined in greater detail.

In the United Kingdom in March 1997, the Secretary of State for the Environment upheld a decision by the Cumbria County Council to refuse a planning application for a rock-characterization facility (RCF) at Sellafield. The purpose of the RCF was to investigate the geology and groundwater regimes in the vicinity of a proposed site for disposing of intermediate-level nuclear waste. The Secretary's decision has resulted in an in-depth reexamination of nuclear waste disposal policy and its implementation in the United Kingdom.

In France, following an unsuccessful effort to site a repository and a reevaluation of the entire process by the Parliament through the work of a nuclear waste negotiator, a process has been established in which three communities have volunteered to have research done at sites within their boundaries.

None, however, has committed to hosting a permanent repository.

In Sweden, efforts to locate five volunteer communities have met with "No" answers in referenda in two communities so far. Three other communities are in the early phases of multiphase feasibility studies, and efforts are under way to locate other volunteer communities.

In all countries where efforts are under way to find and characterize potential repository sites, the process is painstaking and laborious and could take longer than the estimates in current schedules.

X. Congressional Activities

On February 5, 1997, Board Chairman Jared L. Cohon testified on the Nuclear Waste Policy Act of 1997 (U.S. Congress Senate 1997) on behalf of the Board before the Senate Committee on Energy and Natural Resources (Cohon 1997a). In addition, Dr. Cohon commended the DOE for completing construction of the underground ESF. He noted that information recently obtained from the ESF indicates that more water may be percolating through the site than previously anticipated. The Board recommended construction of a 1,200-m-long tunnel, starting at the ESF and extending west directly into and across the proposed waste-emplacement area. Such a tunnel will provide direct access to the relevant geology and will help in addressing uncertainties.

Chairman Cohon also represented the Board at a hearing before the House Subcommittee on Energy and Power, Committee on Commerce (Cohon 1997c). Dr. Cohon presented the Board's comments on legislation pending before the Committee on nuclear waste disposal. He told the Subcommittee that members of the Board take a long-term view of nuclear waste management. The determination of Yucca Mountain's suitability will hinge on results from highly technical analyses. Because we are dealing with periods of thousands of years, these results will include uncertainty, thus requiring technical judgments on the basis of which conclusions will be drawn. The acceptability of these conclusions will depend, in part, on the public's confidence and trust in the objectivity of the process.

XI. Changes in Membership of the Nuclear Waste Technical Review Board

A. New Board and Chairman

In early 1997, President Bill Clinton appointed eight new members to the Board and designated Jared L. Cohon, one of three continuing members, chairman.

Dr. Jared L. Cohon, who was appointed to the Board in June 1995, is president of Carnegie Mellon University in Pittsburgh, Pennsylvania. He brings to the Board expertise in environmental systems analysis and hydrology. He is former dean of the School of Forestry and Environmental Studies at Yale University and also was professor of environmental systems analysis and mechanical engineering at Yale.

Dr. Daniel B. Bullen was appointed on January 17, 1997. He is coordinator of the nuclear engineering program and associate professor of mechanical engineering in the Department of Mechanical Engineering at Iowa State University in Ames, Iowa. His areas of expertise include performance assessment modeling and materials science.

Dr. Florie A. Caporuscio was appointed on January 17, 1997. He is a geochemist with Benchmark Environmental Corporation in Albuquerque, New Mexico. His field of expertise is disposal of high-level and transuranic radioactive waste. Dr. Caporuscio resigned effective June 24, 1997. As of the date of printing this report, the President had not appointed a replacement for Dr. Caporuscio.

Dr. Norman L. Christensen, Jr., was appointed on January 17, 1997. He is a professor and dean of the Nicholas School of the Environment at Duke University in Durham, North Carolina. His areas of expertise include biology and ecology.

Dr. Paul P. Craig was appointed on January 31, 1997. He is emeritus professor of engineering at the University of California at Davis and is a member of the UC Davis Graduate Group in Ecology Environmental Policy. His area of expertise is energy and environmental policy.

Dr. Debra S. Knopman was appointed on January 17, 1997. She is director of the Center for Innovation and the Environment of the Progressive Policy Institute in Washington, D.C. Her areas of expertise include hydrology, environmental and natural resources policy, systems analysis, and public administration.

Dr. Priscilla P. Nelson was appointed on January 17, 1997. She is program director of the Directorate for Engineering of the National Science Foundation (NSF) and chairs the NSF Working Group on Civil Infrastructure Systems. Her areas of expertise include rock engineering and underground construction.

Dr. Richard R. Parizek was appointed on February 11, 1997. He is professor of geology and geoenvironmental engineering at The Pennsylvania State University and president of Richard R. Parizek and Associates, consulting hydrogeologists and environmental geologists. His areas of expertise include hydrogeology and environmental geology.

Dr. Alberto A. Sagüés was appointed on January 17, 1997. He is professor of materials engineering in the Department of Civil and Environmental Engineering at the University of South Florida. His areas of expertise include corrosion and materials engineering, physical metallurgy, and scientific instrumentation.

In addition to Dr. Cohon, the following two members appointed by President Clinton in his first administration continue on the Board.

Mr. John W. Arendt was appointed in June 1995. Mr. Arendt is senior consultant and founder of John W. Arendt Associates, Inc., and is a member of the Nuclear Standards Board. His areas of expertise include nuclear materials facilities and their quality assurance, quality control, and inspection.

Dr. Jeffrey J. Wong was appointed in June 1995. He is a toxicologist with the California Environmental Protection Agency. His areas of expertise include risk assessment and scientific team management.

B. New Panel Structure

The Board uses various combinations of its members, formed into focus panels, to perform its mission. In April, the Board restructured its panels into five new focus areas chosen to reflect the major categories of technical and scientific issues expected to face the Yucca Mountain project for the next few years.

The Panel on Site Characterization is chaired by Dr. Debra Knopman and includes Dr. Priscilla Nelson, Dr. Richard Parizek, and Dr. Alberto Sagüés. The panel's mission is to review all on-site and laboratory studies of the suitability of the Yucca Mountain candidate repository site and to evaluate the adequacy of the hydrology, radionuclide transport, and other process models that are the foundation for a total system assessment of repository performance.

The Panel on the Repository is chaired by Dr. Priscilla Nelson and includes Mr. John Arendt, Dr. Daniel Bullen, and Dr. Alberto Sagüés. Its mission is to review repository design activities and plans for repository construction, operation, and closure. The panel also reviews the development of waste package and engineered barrier designs, supporting testing activities, and source-term and other process models that support a total system assessment of repository performance.

The Panel on the Waste Management System is chaired by Mr. John Arendt and includes Dr. Daniel Bullen, Dr. Norman Christensen, Dr. Paul Craig, and Dr. Debra Knopman. Its mission is to review the major components of the waste management system except the repository, especially the transportation infrastructure needed to move spent nuclear fuel. The panel also reviews systems analysis and integration activities within the DOE program.

The Panel on Performance Assessment is chaired by Dr. Daniel Bullen and includes Dr. Paul Craig, Dr. Richard Parizek, Dr. Alberto Sagüés, and Dr. Jeffrey Wong. Its mission is to review the models, data, and computational methods used in the DOE's total system performance assessment; to understand the applicability and weaknesses of the models; and to build the foundation for continued evaluation of performance assessment iterations.

The Panel on the Environment, Regulations, and Quality Assurance is chaired by Dr. Jeffrey Wong and includes Mr. John Arendt, Dr. Norman Christensen, Dr. Paul Craig, and Dr. Debra Knopman. Its mission is to review environmental monitoring at Yucca Mountain and preparation of an EIS for the site, evaluate regulations applicable to the program and the potential effects of regulatory changes on the program, and monitor the adequacy of the DOE's quality assurance programs for Yucca Mountain.

Chapter 2

What Happens When Radioactive Waste Reaches The Water Table?

The suitability of the candidate repository site at Yucca Mountain is expected to be evaluated in large part on the basis of projected radiation doses or health risks to people who might be exposed to releases from the facility. The doses or health risks depend primarily on the *concentrations* of radionuclides entering the biosphere. Many factors influence radionuclide concentrations, including the performance of engineered barriers and the characteristics of the unsaturated zone between the repository and the underlying saturated zone. This chapter discusses the fate of radionuclides *after* they reach the water table (the upper limit of the saturated zone)—that is, their transport through the geologic barriers of the saturated zone and through the biosphere to humans.

I. The Saturated Zone

A. Overview of Regional Groundwater Flow in the Saturated Zone

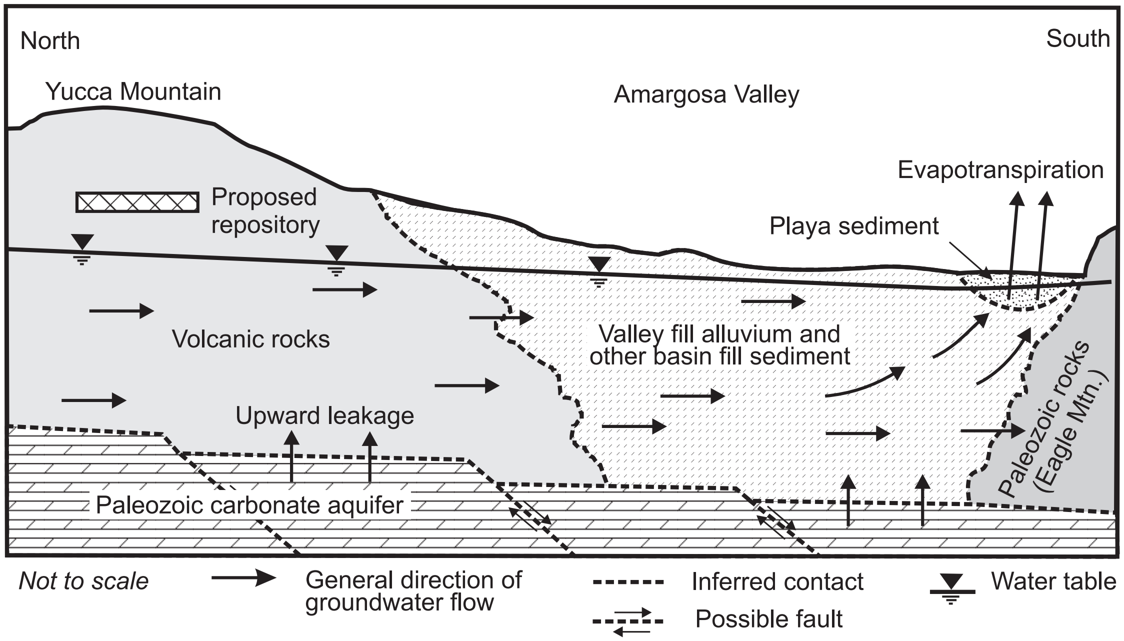
The water table at Yucca Mountain lies between 500 and 700 m below the surface. The dominant recharge of water to the saturated zone occurs farther north at higher elevations, where the precipitation is greater and the temperatures are lower. The *percolation flux*, or the rate at which water moves down through the unsaturated zone[19] at Yucca Mountain (on the order of 10 millimeters per year [mm / yr]), is small in comparison to the groundwater flux in the saturated zone below Yucca Mountain. Although there is a large uncertainty and variability of flow in the saturated zone with depth, the average flux is on the order of 1 m / yr.

The dominant flow direction in the saturated zone from the potential repository site in Yucca Mountain is southeast below Fortymile Wash (which also is an active recharge area), then south to Amargosa Valley (D'Agnese et al. 1997). The primary hydrogeologic units that carry and influence the flow are the aquifers in the volcanic rocks beneath Yucca Mountain, the much older Paleozoic carbonate aquifer, and the valley fill alluvium (see Figure 2).

On the basis of water-pressure data and modeling, the general belief is that the downgradient flow paths emanating from Yucca Mountain primarily stay within the aquifers and, farther south, within the valley fill alluvium. The flow paths originating from Yucca Mountain probably do not penetrate the carbonate aquifer around Yucca Mountain. The principal basis for this conclusion is evidence of elevated heads within the carbonate aquifer in the Yucca Mountain area. There are few data to the southeast of Yucca Mountain that support or argue against this interpretation, and it is possible that the flow paths enter the carbonate aquifer at distances

19. Although percolation flux appears here in units of velocity, flux is the *volume* of water moving across a *unit area* per *unit period of time*.

Figure 2. Idealized Geohydrologic Cross Section from Yucca Mountain to Amargosa Valley



Source: After Czarnecki 1989

of 10 km from the site and then rise back into the volcanic rocks and alluvium farther downgradient.

Because the region has been tectonically active, the regional hydrogeologic environment is structurally complex and is characterized by high permeabilities that are due to faults and fractures. Most of the flow appears to be channeled into preferential flow paths that, according to flow-meter data, appear to represent only 5 to 20 percent of the thickness of the hydrostratigraphic units. The role of the major faults and fracture systems is considered very important. However, because the locations of the faults and their hydrologic properties are not well known, predictions are not well founded.

B. Conceptual Model of Radionuclide Transport and Dilution in the Saturated Zone

Because the saturated zone is characterized by highly fractured transmissive regions, groundwater travel times through it to the accessible environment 20 to 30 km away are difficult to quantify. Isotopic age-dating of groundwater downgradient of Yucca Mountain indicates that the water may have taken several thousand years to get there from Yucca Mountain. Hydrologic-based estimates generally yield shorter travel times, and there is a distinct possibility that the shortest travel times could be less than 1,000 years. Nevertheless, the saturated zone has been viewed as a potentially important natural barrier, primarily because of its potential for “dilution.” In this case,”dilution” is defined as a decrease in radionuclide concentration.

The important saturated zone processes affecting radionuclide concentration are conceptualized as follows: (1) mixing with radionuclide-free water at the boundary between the unsaturated and saturated zones, (2) spreading of the radionuclide plume by molecular diffusion and hydrodynamic dispersion during flow to the accessible environment, and (3) retardation and spreading of radionuclides due to sorption on mineral surfaces. All three of the natural processes are being investigated for their dilution potential as the radionuclide plume flows to the accessible environment some 5 to 30 km away.

In addition, very significant dilution can occur at an extraction well, the primary pathway for human exposure. Because groundwater extraction is a human activity, it is generally treated separately from the natural barriers as part of biosphere modeling.

C. Mixing and Dispersion

Resolving uncertainties about mixing and dispersion of radionuclides in the saturated zone is technically difficult, and uncertainties may not be resolvable in the near future. Current understanding suggests that the plume entering the saturated zone will stay largely intact. Lateral spreading and dilution through molecular diffusion and hydrodynamic dispersion are likely to be limited.[20] The path of the plume will be difficult to predict because of the lack of detailed knowledge of the hydraulic and transport properties of the saturated zone, particularly the properties related to faults between Yucca Mountain and Amargosa Valley.

D. Retardation

Some of the principal transport parameters used by the TSPA are the retardation factors for specific radionuclides. These factors quantify the potential of specific radionuclides to sorb, or bind, onto specific mineral surfaces. For a given porous material saturated with water containing a concentration of a specific radionuclide, a retardation factor can be determined in a laboratory experiment. The net effect of sorption is to retard the velocity of the radionuclide relative to that of the water by a factor of R ($R>1$); that is, if the velocity of the groundwater is v, a radionuclide will have an effective velocity of v/R.

Plutonium sorbs very effectively on many mineral surfaces and thus has a very high retardation factor ($R \sim 100$). Technetium and iodine, on the other hand, are essentially unretarded ($R \sim 1$). Neptunium is another critical radionuclide and has a retardation factor in the range ($1< R<10$). Thus, the predicted travel time of plutonium is several orders of magnitude longer than that of technetium and iodine.

Because plutonium sorbs so effectively and has such a high retardation factor, it appears, at first sight, incapable of long-range transport over reasonable time scales. Because of plutonium's strong propensity to sorb, however, it can attach itself to colloids (very fine suspended particles) in the groundwater and be transported along with the colloid. The possibility of this mechanism for plutonium transport is being investigated at the Nevada Test Site, in particular near the Benham nuclear test area, some 40 km north of Yucca Mountain.

Whether retardation will be as effective in situ as predicted by laboratory experiment is a difficult question to answer because the saturated zone is highly variable in its hydraulic and mineralogic properties. What is known is that highly transmissive (fractured) regions exist and can carry most of the flow. Estimates of how much sorption and retardation will occur in these highly transmissive regions are uncertain. Retarding (sorptive) minerals generally are very fine-grained (e.g., clays) and form very-low-permeability layers or clusters. Only if they extensively coat fracture surfaces can they be effective. The bulk of the flow may effectively bypass these sorptive minerals. Some retardation also may occur if radionuclides diffuse into the rock matrix adjacent to fractures and faults. The extent to which this process can be relied on to reduce radionuclide concentrations still has not been determined adequately.

E. Conclusions

The effect of molecular diffusion, hydrodynamic dispersion, and sorption on dilution in the saturated zone is very hard to quantify. The most direct way to obtain an answer is to perform large-scale tracer tests—that is, tests in which tracers are injected into the saturated zone at Yucca Mountain and are monitored in wells at the locations (5 km or more distant)

20. Members of the expert panel on the saturated zone (discussed in Chapter 3) were asked to estimate a dilution factor for Yucca Mountain. The average estimate for a dilution factor from the three experts, of the five on the panel, who provided this information was approximately 10.

where future populations are assumed to be exposed. Such tests are impractical in the near term because it could take a very long time for the tracers to travel from Yucca Mountain to the monitoring wells. Thus, the additional dilution that the saturated zone can provide (above a factor of 10) through natural processes is uncertain and will remain so for some time. Although some data may be obtained from the proposed saturated zone test facility, which will be located south of the proposed Yucca Mountain repository, reducing this uncertainty will be very difficult.

II. Interface of Geosphere and Biosphere

A. Seeps and Springs

Many seeps and springs occur naturally in Amargosa Valley, indicating the active discharge of water to the surface. In addition, there are remains of paleo-spring deposits closer to Yucca Mountain, indicating a much higher water table (~80 to 100 m higher) during wetter climates in the past. The absence of such paleo-spring deposits at even higher elevations at Yucca Mountain suggests a limit on the maximum height of the water table in the past. The Ash Meadows discharge area, at the eastern edge of Amargosa Valley, is believed to be the discharge from a deeper aquifer (the carbonate aquifer) brought to the surface by means of connecting fractures or faults.

Human contact with water discharging from springs is a potential mode of exposure to radioactive materials released from a Yucca Mountain repository. For example, at Ash Meadows, spring water has been used for swimming and for irrigation. Where natural evapotranspiration processes occur (e.g., playa lakes and irrigated crop lands), the concentrations of radionuclides may increase to levels substantially higher than the concentrations of the same radionuclides in an aquifer.

B. Well Withdrawal

The primary interaction of the geosphere with the biosphere occurs through groundwater withdrawal from wells for agricultural uses, such as irrigation of farms and consumption by domestic animals, or other water uses, such as drinking water for humans. Other interactions also are possible, such as uptake by aquatic fauna, external contamination, and inadvertent ingestion. In addition, water has been drawn from springs. This practice is likely to continue in the future.

As described above, there is some reduction in peak radionuclide concentration in the saturated zone, but, according to the expert panel discussed in Chapter 3, it is not expected to be very significant, perhaps a factor of 10 or so, 30 km downgradient of Yucca Mountain. There is a potential for a larger "dilution" effect during well withdrawal. Because the radioactive plume can remain localized, the concentrations in the withdrawn water could be high if a well draws water only from the plume. If the water is withdrawn from a well over a large vertical interval or perhaps from two depths, the withdrawn water will be mixed and could exhibit lower average concentrations.

This concept could be extended, and the average concentration of radionuclides in the water withdrawn from several wells (or perhaps all of the wells in an area) could be used to estimate dilution that is due to well withdrawal. Thus, the concentrated plume would be mixed with a much larger volume of uncontaminated water, yielding a much lower average concentration of radionuclides. In this way, there could be a difference of several orders of magnitude in concentration of radionuclides between water that is sampled directly from the plume and water that is mixed from multiple aquifers or wells.

C. Conclusions

Considerable dilution could occur during groundwater withdrawal. The capture zone of a well could be much larger than the plume, so the plume could be mixed with a considerable amount of uncontaminated water (e.g., the production can be from several intervals, while the contaminated water is localized in a single interval). Thus, even when the plume is basically intact, this process of mixing at the wellhead could produce significant dilution (possibly up to several orders of magnitude), *depending on the specifics of withdrawal*. In some cases, the pumped water from several wells could be mixed. Thus, the dilution from this process could be quantitatively greater than the dilution that occurs through natural processes.

III. The Biosphere

A. Pathways

Radionuclides released from a Yucca Mountain repository could reach humans through a variety of pathways. The simplest, the drinking water pathway, involves using a contaminated source of groundwater as drinking water. Other pathways may be more complex, such as the pathway leading to ingestion of milk by humans. Contaminated groundwater could be used to irrigate crops, and, in time, radionuclides could accumulate in the soil. Radionuclides could enter crops both through direct deposition of contaminated irrigation water on the leaves of the crops and through uptake by roots from contaminated soil. Crops contaminated with radionuclides might be fed to dairy cows, which also might drink contaminated well water. Milk from the cows then might be consumed by humans, perhaps after processing, after blending with milk from other sources, or after conversion to cheese or other dairy products.

Mathematical models of the transfer of radionuclides through pathways have been developed (Smith et al. 1996, Klos et al. 1996). Transfers of radionuclides through pathways are approximated by transfer factors. One type of transfer factor, a concentration ratio, models the transfer of radionuclides as an instantaneous process that maintains a constant ratio of the radionuclide concentrations in two parts of the pathways. For example, the concentration of a radionuclide in fish is modeled as a constant ratio of the concentration of the same radionuclide in the water in which the fish live. Other transfer factors model the transfer of radionuclides on the basis of physical movement of materials. Thus, the daily rate of transfer of a radionuclide from plants to a dairy cow would be the amount of fodder eaten each day by the cow multiplied by the concentration of the radionuclide in the fodder.[21]

Several pathways exist in the vicinity of Yucca Mountain through which radionuclides released to the biosphere could cause radiation doses to humans. The DOE is modeling the pathways by using an existing computer code, GENII-S (Leigh et al. 1993, Napier et al. 1988), that uses transfer factors of the types described above. The DOE is using mostly "generic" data derived from the scientific literature as the source of transfer factors, but some site-specific data are available from the Nevada Test Site. The DOE also has completed a survey of people living near Yucca Mountain to determine their dietary habits, especially the amounts of locally produced foods they consume.

In many cases, generic data will be adequate for biosphere modeling at Yucca Mountain. For example, there is no reason to believe that the amount of fodder consumed daily by dairy cows near Yucca Mountain is much different from the amount consumed by dairy cows elsewhere. However, some data will be highly site specific, especially the uptake of radionuclides by plants from soil. Using generic data for such parameters may cause the resulting estimates of radiation dose to be uncertain by three or four orders of magnitude, or by a factor of 1,000 to 10,000 (Smith et al. 1996). The importance of collecting site-specific data, relative to the importance of other sources of uncertainty, should be assessed.

B. Conclusion

In general, the DOE's approach to modeling seems appropriate. However, there are opportunities to improve the data set used for modeling, especially to support a later license application.

21. A transfer function also is needed to describe the fraction of radionuclides ingested by the cow that is transferred to her milk.

C. Recommendation

The DOE should evaluate the need for site-specific data for supporting the biosphere modeling needed for a license application, especially soil-to-plant transfer factors. The evaluation should include an estimate of the length of time over which measurements of such parameters would be needed to produce a reliable data set. Plans should be developed now to obtain the necessary data.

Chapter 3
Expert Judgment

I. Introduction

Beginning with its first report (NWTRB 1990a), the Board observed that many critical issues associated with the assessment of the proposed Yucca Mountain repository could not be resolved by data collection alone. Even when collection of additional data can help resolve difficult issues, program decisions often have to be made before the additional data can be collected. The TSPA-VA discussed in Chapter 1 is, in reality, an analysis that is based on an incomplete data set. Whether one is dealing with the inherent uncertainty associated with scientific understanding or the need to make an assessment before all the relevant data have been collected, *expert judgment*—implicit or explicit, formal or informal—is bound to play a vital and central role.[22]

In 1991, the Board recommended that the DOE convene a workshop on expert judgment and develop guidelines for its use. The Board also expressed its concern that any methodological differences with the NRC be resolved before hearings on repository licensing begin. Much progress has been made on these recommendations. The DOE convened the workshop in 1993, developed guidelines similar to those developed by the NRC, and has initiated seven expert elicitations over the last 2 years on different subjects.

II. Why Elicit Expert Judgment?

The central purpose of each elicitation has been to (1) evaluate the relevant data and models (to the extent that they exist) in a particular area of interest and (2) characterize the data and the models, particularly their uncertainties, in a way that is both representative of the views of the informed technical community at large and useful to the Yucca Mountain program.

Two of the recent elicitations, on volcanic hazard and seismic hazard, were aimed at final resolution of important issues, and five—on unsaturated zone flow, saturated zone flow and transport, waste package degradation, waste form degradation and radionuclide mobilization, and near-field / altered-zone coupled effects—focused on the immediate needs of the TSPA-VA. Past TSPAs have made extensive use of expert judgment in defining the models, assumptions, and parameters needed to carry out the required calculations.

In many, perhaps most, cases, letting "the data speak for themselves" is simply impossible. The data must be screened, interpreted, and often extrapolated to be of practical use. For example, the measured hydraulic conductivity at one or more locations or depths is not necessarily appropriate for use at other locations or depth. Tests involving corrosion of metals conducted over several years have little value for performance assessment unless they can be extrapolated to determine corrosion rates over hundreds

22. "Expert judgment" can be defined as an inference or an evaluation that is based on an assessment of data, assumptions, criteria, and models by one or more experts in a field.

and thousands of years. Judgment is required. In most programs and technical endeavors, the vast majority of the judgments has been informal, usually accompanied by the analyst's rationale.

Starting with TSPA-91 (SNL 1992), attempts were made to formalize some of these judgments through a process of structured elicitation. These elicitations involved performance assessment analysts asking one or more of the scientists working on the project for their views on the central estimate and uncertainty distribution of the parameter in question. Some of the elicitations were more structured than others, as was the determination of sorption parameters for TSPA-91, and sometimes they were merely letters sent by the scientists to the analysts that contain opinions on issues, as was done in estimating the extent of galvanic protection for TSPA-95 (McCright 1995).

For the TSPA-VA, a more formal procedure was determined to be appropriate. The procedure involves both the use of individuals experienced in eliciting expert judgment and the use of experts outside the DOE and its contractors. This approach is intended to give the Yucca Mountain project the fresh perspective and depth of knowledge needed to increase both the level of expertise and the program's credibility.

III. General Comments

Board members and staff attended all of almost 30 open meetings and field trips conducted for the 7 expert elicitation panels. In addition, the Board invited individual experts from completed elicitations to Board meetings to provide their views on key technical issues and the elicitation process itself.[23] These interactions were very enlightening. Overall, the Board strongly believes that these recently completed and ongoing expert elicitations have proven very useful to the Yucca Mountain project itself and to those trying to evaluate it. The following general conclusions can be drawn.

- **The elicitations have provided a fresh, outside, perspective on important issues.** Perhaps the most important contribution of the recent expert elicitations has been the systematic exposure of key models, assumptions, and parameters to experts not directly involved in the Yucca Mountain project.[24] Although permanent external review groups, such as the NRC and the Board, have examined the program, they often cannot bring to bear the depth of technical expertise on a particular issue provided by a group of national (and occasionally international) scientists and engineers who are known specialists in a field. Sometimes, such expertise can be found in specially formed peer review groups, such as those convened by the DOE and the National Academy of Sciences. These groups usually end up with lists of recommendations for further research by the project, but they usually do not provide insight on how to represent specific uncertainties, given the existing knowledge base. In addition, there is no better impetus for thoughtful evaluation than when one has to provide identifiable judgments on the specific use of uncertain, and often controversial, interpretations of information.

- **The elicitations and their incorporation in probabilistic calculations have helped sort out the significance of controversial issues**. Very often, scientists within the Yucca Mountain project and those reviewing it have been involved in lengthy debates about scientific issues. The expert elicitations involved examining these issues, particularly in workshop discussions. Workshops are public meetings where the experts and invited specialists discuss the data and issues. The discussions, sometimes accompanied by preliminary probabilistic calculations, have helped define which of the issues are important to assessing the safety of the project and which are not. Probably

23. By the end of 1997, experts from the panels addressing volcanic hazard, unsaturated zone flow, and waste package degradation had made presentations to the Board.

24. The proportion of outside experts in a particular elicitation varied from 50 to 100 percent, depending on the issue being considered.

the best examples of this process are the elicitations on volcanic hazard and on flow and transport in the saturated zone.

- **The elicitations conducted solely for the TSPA-VA often were limited by insufficient time and number of experts.** The five expert elicitations that focused on the immediate needs of the TSPA-VA were limited to three workshops each. Thus, for example, the important process of feedback—that is, recalibration by the experts after initial input has been provided—was not facilitated by group discussion, where detailed individual-input models and parameter distributions are subjected to the give and take so important in scientific assessment. A limited budget and the tight schedule dictated by program considerations (for example, having the VA ready by the fall of 1998) constrained the elicitation process. The small number of experts (five to seven) involved in each of the TSPA-VA elicitations and the breadth of the fields covered by each elicitation sometimes resulted in only one or two experts being willing or able to provide input on some of the questions being asked. Although having input from one or two outside experts is better than having input from none, there is less confidence that robust estimates of uncertainty are being provided than if the estimates of uncertainty are based on the input of five or more experts. The DOE needs to address this issue.

- **The difficult, yet important, task of when and how to combine expert judgments needs to be addressed fully**. Combination or aggregation of expert judgments is an issue that is of interest to decision analysts.[25] Whether to combine these judgments depends often on the analysts' views of whether degree of belief is something that can be dealt with mathematically. If aggregation is considered appropriate, one is faced with the choice between mechanical aggregation of these views through some mathematical formula and behavioral aggregation that relies on personal interactions and consensus building to combine expert judgments. The expert-elicitation studies discussed here relied on both approaches: mechanical aggregation, applying equal weight to individually elicited judgments, which, in turn, are based on a series of workshops—that is, behavioral aggregation, where personal interaction and the range of technical issues being considered were encouraged and facilitated. Whenever expert judgments are combined and whatever the method of combination, a rationale must be presented and, as stated in Kotra (Kotra et al. 1996), "Regardless of which aggregation techniques are ultimately selected … sufficient documentation must be provided to trace the impact of each individual subject-matter expert's judgment on the consolidated position." The completed expert elicitations generally have followed this advice. Not yet clear, however, is how the results of the individual elicitations will be used in the TSPA-VA and to what extent individual views will be considered only as part of a combined estimate or also will be treated separately in sensitivity studies. The DOE has to present a clear rationale for whatever course it takes.

- **Does the use of expert judgment hinder the collection of important data?** One of the frequently stated concerns about the use of expert judgment has been the fear (restated by the TSPA peer review panel in its second interim report [TSPA Panel 1997b]) that it would serve as an excuse to stop meaningful data collection. Thus far, this has not proven to be the case. In fact, many of the experts in the different panels called attention to the lack of important data in different areas. This is particularly true of the experts on the panels for the unsaturated zone, the saturated zone, and waste package degradation. It has been much less so of the panel on volcanic hazard. This dichotomy is not so much due to the experts, but it rather reflects the state of data gathering and its relationship to the point of diminishing returns in understanding key issues related to repository performance.

25. This is an especially important issue when there are relatively few experts and they exhibit sharp, and significant, disagreement

- **How should the results of an expert elicitation be viewed in light of new data?** The results of any elicitation can depend very much on the data available at the time of the elicitation. New data may, or may not, affect the judgments. The sponsoring organization (in this case, the DOE) has various options, including assessing the effect of the new data, overriding the results of the elicitation, and reconvening the expert panel. The DOE already has been faced with the problem of new, post-elicitation, data on volcanic hazard and waste package degradation. Undoubtedly, new data will continue to be collected. The DOE should consider defining guidelines on how the results of expert elicitations should be treated in light of such data.

Below is a summary of each recent expert elicitation.

IV. Results from Individual Expert Elicitations

A. Volcanic Hazard

1. Objectives and Key Issues

The first of the recent expert elicitations was conducted in 1995 and 1996 on volcanic hazard. Its aims were to assess the probability of disruption of the proposed Yucca Mountain repository by a volcanic event and to quantify the uncertainties associated with the assessment. This study, also known as the "probabilistic volcanic hazard analysis," or PVHA, has been a topic of much discussion between the DOE and the NRC. It was highlighted in the general scientific press (Kerr 1996) and was discussed in the Board's 1996 summary report (NWTRB 1997a).

Volcanic hazard has been a high-visibility topic for the scientists working on or concerned with the suitability of the Yucca Mountain site. The prospect of a volcanic intrusion into the repository has been viewed as an undesirable high-consequence event, one of the few occurrences that could result in the direct and immediate transportation of radioactive waste to the surface. No serious argument was presented by any of those involved that such an intrusion can be categorically ruled out. It has long been realized that the *likelihood* of this intrusion eventually would determine its significance to the Yucca Mountain project.

Volcanic studies of the Yucca Mountain area began in 1979 and have been surrounded by much scientific controversy, particularly in the last 10 years. The controversies have included the following:

- **The age of the most recent volcanism at the youngest nearby volcanic center (Lathrop Wells)**. Different investigators using different age-dating techniques estimated the time of the most recent volcanism near Yucca Mountain at anywhere between 140,000 years to less than 10,000 years ago. Los Alamos National Laboratory (LANL), the primary DOE contractor for volcanic studies, was the main proponent of the lower estimate.

- **The mode of volcanic activity**. LANL scientists maintained that, on the basis of geochemical evidence and different age-dating techniques, volcanic activity was *polycyclic*—that is, multiple eruptions over tens of thousands of years at the same location but from different sources. Others argued that, on the basis of paleomagnetic and certain age-dating studies, volcanic activity (particularly at Lathrop Wells) was *monogenetic*—that is, a single episode of eruptions from the same source, closely spaced in time.

- **Structural control of past and future volcanic activity**. LANL scientists maintained that, because past volcanic activity had occurred primarily in and around Crater Flat (west of Yucca Mountain), there is an extremely high likelihood that if there is any volcanic activity in the next 10,000 years, it will occur there. Others argued that the orientation of faults and the occurrence of volcanic activity several million years ago at Buckboard Mesa (east of Crater Flat and north of Yucca Mountain) suggest that Yucca Mountain itself should be included in a zone of future volcanic activity.

- **Probabilistic models of volcanic activity.** LANL scientists proposed that the most appropriate way of treating volcanic activity is to assume that it would occur randomly (that is, unpredictably) in space and time within a defined zone. Other scientists maintained that complete randomness in a zone is unwarranted and that spatial and temporal trends must be taken into account.

There was a general feeling, supported by some initial LANL estimates, that most of these issues had little effect on the estimates of hazard. One of the most important tasks of the expert panel was not only to address these disputes but, in doing so, also to establish a credible basis for probabilistic calculations that could be used to assess the significance of the different issues. The experts[26] covered the range of disciplines needed to address volcanic hazard (geology, geochemistry, and geophysics). Over the course of a year, they participated in four workshops and two field trips. They ultimately were asked to provide three basic kinds of information: (1) the locations and ages of past volcanic activity within the Yucca Mountain region, (2) the definition of volcanic zones and spatial and temporal models of future volcanic activity, and (3) the dimensions and orientations of future volcanic events. Each expert was required to describe the uncertainty associated with each input and was encouraged to provide alternative models as deemed necessary.

The company contracted by the DOE to conduct the expert elicitation then integrated these input parameters into hazard curves describing the likelihood of volcanic intrusion into the proposed repository over the next 10,000 years. The experts were shown the results of these initial hazard calculations. They met and subsequently provided revisions to their input that were the consequence of interaction with other experts.

2. Results of the Elicitation

A very wide range of models was assumed by the experts, but some trends were clear. The majority view was that the Lathrop Wells Volcanic Center was monogenetic. Directly or indirectly, the experts implied that the last activity was about 100,000 years ago. They defined many possible zones of future volcanic activity, a number of which include the Yucca Mountain site. No one, however, supported a previous contention of a small, high-activity volcanic alignment extending from Lathrop Wells to the proposed repository. Most of the experts supported the assumption of temporal randomness, but many supported some notion of spatial clustering. Of greatest interest were the calculated probabilities of volcanic intrusion into the proposed repository. They ranged from about 10^{-10} to 10^{-7} per year, with an overall arithmetic mean of 1.5×10^{-8} per year. Most (about two thirds) of the uncertainty was due to each expert's own uncertainty rather than to differences in input among experts. One analyst's comment was that these results appear to be due to the fact that there are very few past volcanic events and a wide range of uncertain models that could explain these events. The stability of these results is attested to by the fact that, although several hypotheses favored by LANL geologists were rejected, previous studies by LANL arrived at about the same mean annual probability of volcanic intrusion into the repository.

The experts were asked what kind of new information would cause them to change their assessments significantly. Several answers were offered, including the occurrence of an earthquake swarm indicating volcanic activity and the identification of a 1-million-year-old or younger dike (a vertical wall-like intrusion of volcanic rock cutting across preexisting rock strata) intruding into the proposed repository.

3. Conclusions

In many ways, the expert elicitation on volcanism was a landmark event for the Yucca Mountain project. Not only did the elicitation set a high standard for future elicitations and provide information for future use in the TSPA, but it also provided a great deal of insight on a controversial subject and the importance, or lack thereof, of highly controversial issues. The elicitation was a vehicle for the systematic

26. The expert panel consisted of Dr. Richard W. Carlson (Carnegie Institution of Washington), Dr. Bruce M. Crowe (Los Alamos National Laboratory), Dr. Wendell A. Duffield (U.S. Geological Survey), Dr. Richard Fisher (University of California, Santa Barbara, emeritus), Dr. William R. Hackett (WRH Associates), Dr. Mel A. Kuntz (U.S. Geological Survey), Dr. Alexander R. McBirney (University of Oregon, emeritus), Dr. Michael Sheridan (State University of New York, Buffalo), Dr. George A. Thompson (Stanford University), and Dr. George P. L. Walker (University of Hawaii).

inclusion of a wide range of differing views on volcanic hazard. The experts were eclectic in which models they chose to support and which they did not. Several of the hypotheses proposed by the LANL geologists working for the DOE were not endorsed by the majority of the experts, and several hypotheses proposed by researchers at the Center for Nuclear Waste Regulatory Analyses (funded by the NRC) and at the University of Nevada at Las Vegas (funded by the State of Nevada) were endorsed.

Although several issues related to volcanism and its effect on the proposed repository remain, such as modeling the consequences of a volcanic intrusion if it occurs, volcanism can be considered resolved for most purposes. This is in no small part due to the exposure, discussion, and evaluations provided by the experts and to the resultant hazard calculations that made use of the evaluations.

B. Seismic Hazard

1. Objectives and Key Issues

The largest expert elicitation undertaken thus far for the Yucca Mountain project is on seismic hazard. Its aim is to assess the probabilities of vibratory ground motion (shaking) and fault displacement at the Yucca Mountain site and to quantify the uncertainties in these estimates. This study, known as the "probabilistic seismic hazard analysis," or PSHA, began in 1995, was suspended for a year because of budgetary reasons, and will conclude with a final report in the spring of 1998. The results of the PSHA, curves showing the likelihood of different levels of vibratory ground motion at the repository surface and the likelihood of different levels of fault displacement at different locations aboveground and belowground, will be used both in performance assessment and in design. The probabilistic curves will help define the seismic design of the aboveground and belowground repository elements for the preclosure (100 years) and postclosure (100,000 years) periods.

Two expert panels were convened. The first consisted of six teams, each with three experts (specialists in tectonics, Quaternary geology, and seismicity). Each team addressed seismic source characterization and fault displacement. The second panel consisted of seven seismologists addressing vibratory ground motion—that is, ground-motion prediction models incorporating the effects of the earthquake source, wave propagation, and local site conditions. A review panel consisting of four well-known earthquake researchers is conducting an ongoing review of the project. Six workshops on seismic source characterization and fault displacement, three workshops on vibratory ground motion, and one field trip were held on a wide range of topics.

Many PSHAs have been carried out for critical facilities, including nuclear power plants and dams, and several involved formal elicitation of expert judgment. Although earthquake issues at Yucca Mountain have not been as controversial as volcanic hazard, there has been public concern, and several significant technical issues faced the experts. First and foremost was the estimation of fault-displacement hazard. Fault displacement has been considered for some facilities, such as underground pipelines or railways, but nowhere in the world has the need for estimation for so large an area at such small displacements been addressed. This has proven to be a formidable topic, requiring the convening of a previously unanticipated workshop.

Additional challenges were posed by the possibility of distributive faulting—that is, earthquake-induced rupture—on several nearby faults at the same time. This has been observed at some locations in Nevada. The issue was highlighted by the discovery of volcanic ash from the same eruption in several faults around Yucca Mountain, suggesting that there was volcanic activity and movement on multiple faults at about the same time.

Finally, the experts on ground motion were faced with deriving ground motion for normal faulting[27] in a region where there have been relatively few

27. A normal fault is a downward-dipping fault at which the overlying side of the fault has moved downward in relation to the fault's underlying side.

ground-motion recordings. Ground-motion recordings from the 1992 magnitude 5.5 Little Skull Mountain earthquake, 15 km from Yucca Mountain, pointed out the necessity for new ground-motion models.

2. Initial Insights

All the workshops have been completed, as have the final iterations with the experts. As discussed above, the most difficult problem has proven to be estimating fault displacement. Present indications point to the acceptance of two approaches by the experts on fault displacement. The first one is rooted in the principle of WYSIWYG (What you see is what you get.). That is, estimates of the rate of future fault displacement are based simply on the cumulative past fault offset divided by the age of the fault or rock. The other approach relies on some simple physical models of earthquake faulting.

The seismic source-characterization teams also appear to have rejected the possibility of shallow (less than several kilometers deep) *detachments* being important at Yucca Mountain. Detachments are large, almost horizontal faults that have been observed elsewhere and postulated for Yucca Mountain. Observed near-vertical faults at the surface or in the ESF could merge into a detachment at depth. An earthquake on such a detachment could be larger than indicated by observed fault traces and could cause strong vibratory motion over a wide area, although no historical earthquakes have been known to occur on detachments.

Finally, the ground-motion experts appear to have placed prime emphasis on empirical rather than theoretical predictive models. A sustained effort was made to obtain ground-motion data from normal-faulting earthquakes around the world.

When the experts were asked what new information would significantly change the way they characterize the earthquake sources, several possibilities were cited. The possibilities include a large earthquake on a detachment fault anywhere; discovery of offset surface rocks that, while appearing to be related to earthquake faulting, were actually due to other causes; discovery of a large strike-slip fault in the immediate vicinity of Yucca Mountain—that is, one in which the relative fault displacement on a near-vertical fault is horizontal rather than what has been assumed for those faults bounding Yucca Mountain; and substantially different earthquake-recurrence intervals caused, for example, by significant errors in dating past earthquakes. Most of the faults around Yucca Mountain are assumed to have recurrence intervals on the order of 10,000 years or more. The Ghost Dance fault, which bounds the eastern edge of the proposed repository in its present configuration, was assumed to be completely inactive or a very unlikely location of a future earthquake.

The Board awaits the final results of this important study. Along with the evaluation of consequences of an earthquake, seismic issues are on the way to being resolved at Yucca Mountain.

C. Flow in the Unsaturated Zone

1. Objectives and Key Issues

Lawrence Berkeley National Laboratory (LBNL) and the U.S. Geological Survey (USGS) are developing a model of the unsaturated zone at Yucca Mountain. The model is intended to capture key aspects of the unsaturated zone flow system using all of the data collected for the project. Over the last 10 years or so, USGS scientists have collected precipitation and infiltration data over Yucca Mountain and have developed a map of the *net infiltration flux*, the rate at which water from precipitation enters the soil or rock below the surface plant zone. This water then percolates downward, reaching the horizon of the proposed repository. Because the movement of water across the repository horizon is difficult to measure, the LBNL and USGS model will simulate how the infiltrated water percolates down and redistributes itself on its way to the repository horizon. During the last year and a half, the preponderance of evidence has indicated that, on average, the *percolation flux* is an order of magnitude or more greater than the fraction of a mm / yr assumed by the Yucca Mountain project in the past.[28]

Because the unsaturated zone plays such a key role in the overall performance of the potential repository, it was the topic of the first expert elicitation panel convened by the DOE for the TSPA-VA in November 1996. The objective of the expert elicitation was to identify and assess the major data and model uncertainties of the unsaturated zone flow model at Yucca Mountain.

Specifically, the experts[29] were to provide their probabilistic bounds on the modeled percolation flux, which was the primary objective, and on the part of the percolation flux that seeps into the repository (the seepage flux), which was the secondary objective. These two quantities have been identified as most important to the performance of the repository. Estimating the volume of water that can potentially contact the waste packages, corrode the packages, mobilize the radionuclides from the waste form, and then transport them to the saturated zone and the accessible environment is the single most important element of repository performance. In addition, the experts were to evaluate whether the conceptual and numerical models being used are adequate for characterizing the movement of water in a fractured and unsaturated tuff.

2. Results of the Elicitation

The experts considered the nonwelded layer of the Paint Brush tuff formation (PTn) to be an ineffective diversionary barrier to the vertical movement of water over scales of more than a few tens of meters. Thus, the experts concluded that the average percolation flux at Yucca Mountain is essentially equal to the net infiltration flux that occurs at Yucca Mountain. This conclusion reinforced the project staff's current assumption about the effectiveness of the PTn's diversion potential. The assumption is essentially the opposite of the one used by the staff several years ago, which led in part to a waste isolation strategy based on a low percolation flux.

The expert panel provided a combined estimate of average percolation flux at the repository horizon: a mean value of 10.3 mm / yr, a median of 7.2 mm / yr, and a 5^{th} to 95^{th} percentile range of 1.1 to 30 mm / yr. Averages can be somewhat misleading because the flux is temporally and spatially very inhomogeneous. For example, it should not be surprising if the flux is found to be 50 mm / yr or greater in some places and close to zero in others. Also noteworthy is that individual probability distributions varied significantly between experts, depending on the methods and data used. Thus, the assumptions and data used by the experts, in addition to their opinions on the validity of various models and data, had a significant effect on their estimates.

Faults and fractures near the faults play a key role in rapid water transport to the repository horizon. The presence of bomb-pulse (less than 50 years old) ^{36}Cl at depth within the ESF is best explained by fast flow in faults and fractures that occurs during very intense storms. The frequency of such storms is difficult to define with precision but could be as often as every few years or perhaps only every 20 years. However, this fast-flow component was considered a very small fraction, a percent or so, of the total flux.

The consensus was that, because of capillary forces, seepage into the drifts as constructed would be a very small portion (e.g., less than a few percent) of the percolation flux. Although most experts thought that this portion would be very small, there were no data on which to base a quantitative estimate. With increased precipitation and, therefore, increased net infiltration, the fraction of the total flux seeping into the drifts could increase nonlinearly. Thus, a future change to higher-precipitation conditions could cause a more than proportional increase in seepage into drifts and adversely affect repository performance.

3. Conclusions

The elicitation process achieved its stated purpose. On the basis of available data, in some cases quite limited, and models presented to the panel, each panel member provided a probability distribution of the percolation flux at the repository horizon. In addition, they provided quantitative assessments,

28. See the Board's 1996 summary report (NWTRB 1997a).

29. The expert panel was composed of Dr. Gaylon S. Campbell (Washington State University), Dr. Shlomo P. Neumann (University of Arizona), Dr. Glendon W. Gee (Pacific Northwest National Laboratory), Dr. James W. Mercer (GeoTrans, Inc.), Dr. Karsten Pruess (Lawrence Berkeley National Laboratory), Dr. Daniel B. Stephens (Daniel B. Stephens & Associates), and Edwin P. Weeks (U.S. Geological Survey).

and the rationales behind the assessments, of other key issues, such as seepage flux, fast paths, and key data needs. The meetings and subsequent elicitations provided an independent assessment of the status of the unsaturated zone studies in resolving key technical issues. How the project uses this information is a question that remains to be answered.

Several important conclusions can be drawn from the elicitation results. Overall, the unsaturated zone program has made considerable progress in delineating the important boundary conditions and the movement of water at Yucca Mountain. Infiltration and the role of the PTn are better understood and quantified. The probability distribution for the percolation flux, although quite broad because of the many uncertainties, is more realistic than previous assumptions. A better understanding of the bomb-pulse ^{36}Cl data, as well as the age data of the other fracture-coating minerals, has been acquired. All in all, there was considerable agreement on many of the key issues concerning flow in the unsaturated zone.

Several weaknesses also were made more apparent during the process, such as the lack of key data and missed opportunities for acquiring the data. Specifically, the experts were surprised that key data on fluid saturation and water potential were not collected in the ESF during construction, before the ventilation overwhelmed the ambient conditions in the tunnel. Another example is the lack of reliable conductivity data on the PTn unit at ambient saturation, which are essential in bounding the flux through the PTn. Both sets of data would have increased the panel's confidence in its estimates of the percolation flux. The DOE should not miss any opportunity to collect these data in the ECRB program, discussed in Chapter 1.

Three panel members specifically noted that only seven wells provided all of the stratigraphic and core data and that two of the wells had been drilled for other purposes—with core data deemed unreliable (not obtained using approved techniques for quality assurance). One expert commented that there was better well control in most remediation projects in which he had been involved.

The remarks of the panel members about data are constructive. Personnel in the Yucca Mountain project appear to be taking the remarks seriously in planning, for example, the experiments and data collection that will be carried out in the ECRB tunnel across the repository block.

D. Flow and Transport in the Saturated Zone

1. Objectives and Key Issues

The primary performance measure for the repository is expected to be peak individual radiation dose rate. In terms of saturated zone flow and transport, this performance measure is directly related to the peak radionuclide concentrations occurring approximately 20 km downgradient of the repository. Processes that exert the greatest influence on the peak radionuclide concentration in the saturated zone, especially during the first 10,000 years, are most important for performance and were the central focus of this elicitation.

The panel was to consider 16 issues. Three of the most important issues were (1) conceptual model of groundwater flow in the saturated zone beneath the potential repository, (2) evaluation of data (all length scales) on the hydraulic flow-and-transport properties of the saturated zone, and (3) conceptual model of groundwater flow in the saturated zone downgradient of the potential repository. These three issues were considered central to estimating the discharge locations and the amount of dilution in the saturated zone of the radionuclides released from the potential repository.

In addition, other important questions were addressed by the expert panel.[30] Two of the questions were (1) the effects of future climate change on repository performance and (2) the causes and implications of the observed large hydraulic gradient (LHG) north of Yucca Mountain. Finally, the experts

30. The expert panel members were Dr. R. Allan Freeze (R. Allan Freeze Engineering, Inc.), Dr. Lynn W. Gelhar (Massachusetts Institute of Technology), Dr. Donald Langmuir (Colorado School of Mines, emeritus), Dr. Shlomo P. Neumann (University of Arizona), and Dr. Chin-Fu Tsang (Lawrence Berkeley National Laboratory).

were asked for their perspectives on additional data collection or modeling activities that could reduce the uncertainties of the saturated zone flow-and-transport system.

2. Results of the Elicitation

a. Regional and Site-Scale Flow Models.

After reviewing the available data related to the regional and site-scale groundwater flow model, the panel concluded that the dominant flow direction from the potential Yucca Mountain repository site is southeast toward Fortymile Wash and then south to Amargosa Valley. All of the experts expressed a belief that the downgradient flow paths from Yucca Mountain probably occur within the lower volcanic aquifer and, farther south, within the valley fill alluvium. Water that originates at or near Yucca Mountain probably does not flow in the carbonate aquifer underlying the lower volcanic aquifer and valley fill alluvium. This conclusion is based on observations that the heads in the carbonate aquifer at Yucca Mountain are higher. However, there are few data southeast of Yucca Mountain to constrain this interpretation, and the regional groundwater model suggests that, under certain conditions, the flow paths may enter the carbonate aquifer 10 km downgradient of the site and then rise back into the volcanic rock and the alluvium farther downgradient.

In general, the regional hydrologic environment is assessed by the panel to be complex, characterized by high permeabilities, and dominated by faults and fractures that lead to channelized flow. Modeling of such a system can be difficult to validate and is likely to produce results associated with large uncertainties.

b. Dilution and Dispersion

In TSPA-95, the greatest contribution of the saturated zone was its potential for dilution. The conceptual model of transport provided by the experts envisages advective transport along preferential flow paths emanating from beneath the repository and proceeding downgradient within the volcanic aquifer and the alluvium, with little or no flow in the carbonates. Disregarding the potential mixing within the extraction well(s), the experts concluded that few physical mechanisms lead to substantial mixing. A plume is likely to remain largely intact, and the lateral dispersion would be relatively small to distances of 5 to 30 km. Models with substantial mixing depths, such as used in TSPA-95, were considered unrealistic by the panel.

Three experts provided estimated ranges of the dilution factors (overall dilution) for the saturated zone, excluding the possible dilution at the pumped well. The cumulative range was 2 to 100, but the distribution was significantly peaked to the lower values, the median being 12. One estimated range was 2 to 10.

c. Large Hydraulic Gradient

The cause of the LHG has been a controversial issue and has evoked many hypotheses, some quite imaginative. The panel members observed that LHGs are a common feature in the region, as are perched-water bodies, and that they probably share a common cause—that is, they may result from changes in topography, recharge pattern, and geology (highly stratified units that have large differences in hydraulic conductivity). There was a consensus within the panel that the least complex models that are consistent with the available data are most probable. Two such models were presented, both quite similar in their overall flow patterns. Most of the experts also felt that resolving the cause of the LHG is not critical to saturated zone issues, particularly those related to repository performance. Nevertheless, a well is being constructed to address this issue.

3. Conclusions

On the basis of available data, models, and discussions, the experts provided individual probability distributions for the key parameters that are crucial to performance assessment. In addition, the expert panel presented numerous recommendations for reducing uncertainties in the saturated zone modeling. Two of the most prominent are to conduct (1) field tests for helping to determine the hydraulic properties of the faults and fault zones and (2) additional field tracer and pressure-interference tests (in addition to the C-well complex) between boreholes to characterize the hydraulic and transport properties of the geologic units at various scales. The panel expressed a general concern about the lack of data on key hydraulic properties. Considering the importance of the project, the modeling was not generally supported by field data and did not inspire confidence.

E. Waste Package Degradation

1. Objectives and Key Issues

Results from TSPA-95 (TRW 1995) and earlier TSPAs (SNL 1992, 1994) indicate that the waste package will be an important contributor to performance during the first 10,000 years of a repository's life and will continue contributing to performance for some time beyond that period. Except for general corrosion of carbon steel, the results on degradation are based on models derived from very limited data and for conditions that are very different from those a waste package is likely to encounter in a repository at Yucca Mountain. The objective of the expert elicitation on waste package degradation was to characterize the degradation, including uncertainties in the mathematical expressions and the parameters of models planned for use in the TSPA-VA.

The expert elicitation on waste package degradation was conducted over 6 months, beginning in March 1997. The panel consisted of six experts.[31] The principal topics were corrosion of the carbon-steel outer shell of the waste package, corrosion of the nickel-alloy inner shell of the waste package, and the effects of microbially influenced corrosion on either shell. The final report was issued in August 1997 (WPDEE 1997).[32] The expert elicitation was a topic of a session at the Board's October meeting.[33]

2. Results of the Elicitation

a. Carbon-Steel Outer Barrier

The experts generally agreed that the dominant form of corrosion during the period of above-boiling temperatures will be very slow oxidation. There were differences of opinion about the nature and tenacity of the oxide film formed during this period. The experts agreed that the threshold temperature for switching from very slow oxidation to humid-air or aqueous corrosion would be essentially the boiling point of water (perhaps somewhat elevated because of the presence of dissolved salts). The experts agreed that noticeably more rapid humid-air corrosion occurs as the relative humidity increases above a value somewhere between 60 and 80 percent, the exact value depending on surface conditions of the carbon steel (e.g., roughness, dirtiness).

The experts concluded that water dripping onto the waste packages is necessary for aqueous corrosion except when salt deposits are on the waste package. When such deposits are present, aqueous corrosion can occur without dripping water at relative humidities as low as 85 percent. The experts agreed that aqueous corrosion of carbon steel will be uniform except where the water contacting the packages is strongly alkaline (pH>10).[34] Strongly alkaline water might cause high-aspect-ratio pitting (i.e., narrow, deep pits).

The experts generally agreed with the corrosion rates for carbon steel used in TSPA-95, provided that the pH of water contacting the carbon steel is lower than 10. Pit growth at higher pHs could be modeled by a simple pit growth "law" that would

31. The six experts were Dr. Peter L. Andresen (General Electric Corporate Research and Development), Dr. Joseph C. Farmer (Lawrence Livermore National Laboratory), Dr. Brenda J. Little (Stennis Space Laboratory, U.S. Navy), Dr. R. Daniel McCright (Lawrence Livermore National Laboratory), Dr. John R. Scully (University of Virginia), and Dr. David W. Shoesmith (Atomic Energy of Canada Limited).

32. Although the expert elicitation on waste package degradation ostensibly was complete with issuance of the final report on August 15, 1997, a decision was made in December 1997 to convene a supplementary 1-day session of the panel in February 1998 to discuss degradation of inner-barrier materials in light of the recent adoption of alloy C-22. Specific topics to be considered at the supplementary session include new corrosion data and new modeling approaches.

33. Presentations by Dr. Coppersmith, Dr. Lee, Dr. Scully, and Dr. Shoesmith (NWTRB 1997c).

34. Strongly alkaline water might be the result of water flowing through concrete drift liners. In the absence of concrete, strongly alkaline water is unlikely to exist in the repository.

express pit depth proportional to a fractional power of time.[35]

b. Nickel-Alloy Inner Barrier[36]

There was general agreement that localized corrosion is much more important for the inner barrier than general corrosion because general corrosion would be very slow.[37] Localized corrosion could occur through crevice corrosion and possibly by high-aspect-ratio pitting or stress-corrosion cracking. The experts acknowledged that galvanic protection of the inner barrier by the outer barrier is possible but felt that the period of protection is unlikely to be of major significance in comparison to the life of the repository. Because the proposed nickel alloys are modern materials, there are relatively little data or experience with them, particularly in conditions similar to those that would surround a waste package at a repository in Yucca Mountain. The limited data and experience led the experts to express uncertainty in predicting localized corrosion rates.

c. Other Comments from Expert Elicitation Panelists

The experts expressed skepticism about the likelihood that ceramic coatings could be developed that would provide significant additional protection of the waste package. They expressed concern about the potential effects on corrosion of stresses from shrinkfitting, from welding, and from buildup of corrosion products.

Ionizing radiation from the radionuclides will interact with air and water around the waste package, causing chemical species to form (e.g., nitric acid, hydrogen peroxide) that might exacerbate corrosion. The interaction of ionizing radiation with fluids around it is called "radiolysis." Radiolysis is not considered important for repository performance during the period that the waste package is above the boiling point of water. Radiolysis also is not considered important for the period that the waste package is below the boiling point of water (the period following the peak thermal load), because the isotopes principally responsible for ionizing radiation will have decayed away by then.

On balance, the experts were unenthusiastic about replacing carbon steel with monel or cupronickel. They made numerous suggestions for further experimental work to reduce uncertainty, particularly regarding the corrosion of inner-barrier materials.

Except for Dr. Little, members of the expert elicitation panel felt that they did not have a high degree of expertise in microbially influenced corrosion. Thus, the results of the expert elicitation on microbially influenced corrosion were derived essentially from Dr. Little's views. Microbially influenced corrosion will not occur until temperatures are below the boiling point of water and the relative humidity is above 60 percent. When liquid water is not in periodic or constant contact with the waste package, there is unlikely to be sufficient water or nutrients for sustaining microorganisms, so microbially influenced corrosion will be limited or absent. A mass balance calculation for the repository would be useful for understanding limits on nutrient and water flow. The panel noted that alloy C-22 and titanium may be immune from microbially influenced corrosion.

3. Conclusions

The Board believes that the expert elicitation on waste package degradation was worthwhile because it provided the opinions of outside experts to the program and because many of the results of the

35. The pitting corrosion of carbon steel that would take place in strongly alkaline environments is likely to be several times more rapid than general corrosion in mildly alkaline, neutral, or mildly acidic environments. The lifetime of the carbon-steel outer barrier would be correspondingly shorter. The pitting factor "law" would not be extrapolated over long periods.

36. Alloy 625 was the reference alloy for the inner barrier for nearly all of 1997. At the end of 1997, it was replaced by alloy C-22, which possesses superior corrosion resistance in many accelerated-corrosion tests. The basic composition of alloy 625 (in weight percent) is Ni 61, Cr 21.5, Mo 9, Nb 3.6, and Fe 2.5; of alloy C-22, Ni 56, Cr 22, Mo 13, Co 2.5, W 3, and Fe 3.

37. However, quantitative distributions of general corrosion rates elicited from the experts showed a small probability of rapid general corrosion. Presumably, this will be addressed at the February 1998 supplementary session of the WPDEE panel.

expert elicitation are directly and immediately useful for the TSPA-VA. The presentations on the elicitation at the Board's October 1997 meeting indicate that the elicitation results are being taken very seriously for the TSPA-VA. Although the panel furnished much helpful qualitative information about corrosion of candidate nickel alloys for the inner barrier, the quantitative information about inner-barrier corrosion rates varied greatly among panelists. Aggregating this information for TSPA may be difficult.

Essentially, the only way that water dripping onto the waste packages would have a pH higher than 10 would be from incorporation of leachates from the concrete that lines the emplacement drifts.[38] We understand that the DOE is studying the pH of dripping water more closely, and we agree that the issue merits closer study. Concrete formulated for lower-pH pore water and whether concrete drift liners should be used at all also need to be examined. The Board understands that the views of the expert elicitation panel on shrinkfitting, ceramic coatings, and galvanic protection will be adopted for the TSPA-VA base case. However, it is unclear whether the views will be reflected in the waste package reference design that will be included in the VA.

The expert elicitation panel suggested additional laboratory work in localized corrosion. The suggestions focused principally on data needs to support modeling of localized corrosion of the nickel alloy inner barrier. The Board is aware that the suggestions are being examined carefully in the program and that some of them already have been adopted. The Board also is aware that all of the suggestions require further definition.

The Board urges continued examination of the suggestions and their adoption in one form or another. This is particularly important because of the more important role the waste package has attained in the last few years. Making a technically defensible decision on site suitability may not be possible without the additional data that would be obtained by implementing the suggestions of the experts.

F. Waste Form Degradation and Radionuclide Mobilization

1. Objectives and Key Issues

The objectives of the waste form degradation and radionuclide mobilization expert elicitation (WFEE) are to characterize waste package degradation and radionuclide mobilization, identify issues and determine which are key, estimate uncertainties, and assess data needs. "Waste form" means the radioactive waste materials and any encapsulating or stabilizing matrix. For example, for spent commercial fuel, the waste form consists of uranium oxide pellets and the zircaloy cladding surrounding the pellets. For vitrified high-level waste, the waste form is considered the glass "log" itself. (The potential barrier effect of the stainless steel canister into which molten glass is poured for solidification into a log is essentially ignored.) "Radionuclide mobilization" is the physical or chemical transformation of radionuclides in the waste form and their subsequent transport from the waste form to the outer boundaries of the waste package and the entire engineered barrier system.

2. Initial Insights from First Two Workshops

The first WFEE workshop was held on November 18-19, 1997.[39] The second was held on December 15-16, 1997. The third and last workshop is scheduled for January 27-28, 1998. Some insights from the first two workshops are presented below.

- The database on *generalized* zircaloy corrosion and on studies of potential mechanisms for zircaloy

38. Conceivably, "natural" dripping water, which is slightly alkaline, could become more alkaline through concentration because of evaporation if the water drips onto hot waste packages. The change in pH due to concentration of hot water needs to be documented.

39. The panel of experts for the WFEE are Dr. Michael Apted (QuantiSci), Dr. John K. Bates (Argonne National Laboratory), Dr. William Bourcier (Lawrence Livermore National Laboratory), Dr. Lawrence H. Johnson (Atomic Energy of Canada Ltd.), Dr. Henry Shaw (Lawrence Livermore National Laboratory), and Dr. David W. Shoesmith (Atomic Energy of Canada Ltd.).

failure caused by this type of corrosion seems very impressive and clearly sufficient for incorporating in the TSPA-VA. How much performance credit to allow for the cladding will be a difficult decision, however, because (1) a small fraction of the cladding already will have failed during nuclear power plant operation; (2) few data exist for estimating damage (if any) to cladding during storage (particularly dry storage), handling, and transportation before emplacement and the effect of such damage on performance; (3) little study has been done of the potential for cladding damage in an intact container (e.g., by radiolysis of water or air inadvertently trapped in the waste package during loading); and (4) limited study has been done on the degradation of cladding after a waste package is breached (e.g., the cladding could be breached by a rock fall after failure of the inner and outer walls of a waste package). There are essentially no data on the extent of *localized* corrosion of zircaloy under Yucca Mountain conditions.

- The database and level of understanding for the oxidation and dissolution of spent fuel and for the dissolution of vitrified high-level waste seem more than adequate to support development of models for the TSPA-VA.

- As a result of its reexamination of data on neptunium solubility, the Yucca Mountain Project has decided to use a value for neptunium solubility that is two orders of magnitude lower than that assumed in TSPA-95.

- Many questions about colloids remain unanswered. Although definitely known is that colloids are generated by the degradation of glass and spent-fuel pellets, little is known about the variables that affect the *rate* of colloid generation, particularly for spent-fuel pellets. In addition, little is known about how colloids would be sorbed and retarded inside the waste package (e.g., by corrosion products).

G. Near-Field/Altered-Zone Coupled Effects

1. Objectives and Key Issues

Models used in TSPA-95 predicted that the heat from the waste packages would dry out the repository horizon for a long time (i.e., result in above-boiling temperatures but low relative humidities in the emplacement drifts for well over a thousand years) and that these hot and dry environmental conditions would contribute to low corrosion rates and long lifetimes for the waste packages. The predictions, particularly in light of the higher estimates of percolation flux discussed above, have come under question. The central goal of the expert elicitation on near-field / altered-zone coupled effects is to determine the role that thermal processes play in repository performance.

The objective of this expert elicitation is to assess the temporal and spatial distribution of thermal, chemical, mechanical, and hydrologic effects from heating of the host rock by emplaced radioactive waste. The uncertainties in the alternative models and the associated parameters used to evaluate these effects are to be quantified. There are suggestions that chemical or mechanical alteration of the host rock can significantly perturb the near-field permeability and influence repository performance.

The expert panel[40] is addressing the following coupled effects:

- **thermohydrologic**: the redistribution of water during the heating and postheating episode

- **thermomechanical**: stress increase in the host rock, closure of fractures, and drift-stability questions due to the heating episode

- **thermochemical**: mineral alteration due to increased temperatures, or mineral distribution due to dissolution / precipitation reactions mitigated by the redistribution of water

40. The panel members are Dr. Derek Elsworth (The Pennsylvania State University), Dr. John E. Gale (Fracflow Consultants), Dr. Roger D. Hart (Itasca Consulting Group), Dr. Benjamin Ross (Disposal Safety), Dr. Robert S. Schecter (University of Texas), and Dr. Yanis C. Yortsos (University of Southern California).

2. Initial Insights from First Two Meetings

The single-heater test, discussed in Chapter 1, already has produced useful thermohydrologic results: (1) the saturation profile around the heater, the dryout region, is not symmetrical; (2) the saturations above the heater are lower than below the heater, indicating that there is draining around the heater through the fractures. These results already have demonstrated that the equivalent-continuum model[41] does not adequately model the thermally driven movement of water under repository-like conditions.

Although a good case was made by Yucca Mountain project scientists that there would be thermochemical changes in the near field, no evidence was presented that the changes would alter the permeability significantly or how permeability changes would affect performance. The modeling is very detailed and consumes much of the effort devoted to thermochemical effects. Comparatively little effort is expended on the more substantive question, the quantitative relevance of the modeling to repository performance.

V. Conclusions

The DOE is nearing completion of seven expert-elicitation studies on a wide range of scientific and technical issues affecting the Yucca Mountain site. The DOE is commended for carrying out these studies and, in particular, for including a substantial number of outside scientists and engineers on the expert panels. Aside from supplying information that can be used directly for performance assessment and design, these elicitations have provided highly important insights into the program. They include the endorsement or rejection of a number of previously accepted scientific models and design assumptions; an independent assessment of the importance, or lack thereof, of different hypotheses; and establishment of the need to acquire selected additional data. The challenge to the DOE is to make full and effective use of the experts' input.

In making full and effective use of the expert elicitations, the DOE needs to address the potential problem posed by receiving input on several issues from only a small number of the experts who were asked; how it intends to aggregate the views of multiple experts, especially where sharp and meaningful disagreements exist; and how it will treat the results of an elicitation in light of new data. Sufficient information must be presented to trace the effect of an individual expert's judgment on the aggregations of the judgments. The DOE also needs to explain how the views of individual experts will be treated in sensitivity studies for the TSPA-VA.

VI. Recommendation

The DOE should make full and effective use of the expert elicitations, both as direct input to the TSPA and the design and for the technical insights provided. The DOE should provide a rationale for the way it intends to aggregate the views of different experts and how the individual views of the experts will be treated in performance assessment. The DOE also should consider developing guidelines on how the results of expert elicitations will be treated in light of new data.

41. An equivalent-continuum model of flow in fractured rock assumes that the flow properties of both the fractures and the rock matrix can be approximated by assuming a porous medium with gross properties chosen to reflect the presence of fractures.

Abbreviations and Acronyms

AECL Atomic Energy of Canada Limited

Board U. S. Nuclear Waste Technical Review Board

CFR Code of Federal Regulations

^{36}Cl chlorine-36

cm centimeter

CRM corrosion-resistant material

DOE U. S. Department of Energy

DOT U. S. Department of Transportation

DST drift-scale test

EARP Environmental Assessment Review Panel

ECM equivalent-continuum model

ECRB enhanced characterization of the repository block

EIS environmental impact statement

EPA U.S. Environmental Protection Agency

ESF exploratory studies facility

km kilometer

LANL Los Alamos National Laboratory

LBNL Lawrence Berkeley National Laboratory

LBT large-block test

LHG large hydraulic gradient

LLNL Lawrence Livermore National Laboratory

m meter

M&O management and operating contractor

MIC microbially influenced corrosion

mm/yr millimeters per year

MPC multipurpose canister

mrem/yr millirems per year

NAS National Academy of Sciences

NRC U.S. Nuclear Regulatory Commission

NSF U. S. National Science Foundation

NWPA Nuclear Waste Policy Act

NWPAA Nuclear Waste Policy Amendments Act

NWTRB U. S. Nuclear Waste Technical Review Board

PNL Pacific Northwest National Laboratory

PSHA probabilistic seismic hazard analysis

PTn nonwelded Paintbrush Tuff

PVHA probabilistic volcanic hazard analysis

RCF rock-characterization facility

SHT single-heater test

SNL Sandia National Laboratories

SRG scientific review group

TSPA total system performance assessment

TSPA-VA total system performance assessment-viability assessment

URL underground research laboratory

USGS U.S. Geological Survey

VA viability assessment

WPDEE Waste Package Degradation Expert Elicitation

WFEE Waste Form Degradation and Radionuclide Mobilization Expert Elicitation

WYSIWYG What you see is what you get.

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; rather, it is meant to help the reader understand some of the terms used regularly by the Board.

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

aquifer. Permeable saturated rock through which groundwater flows.

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

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

biosphere. The part of the earth that supports self-sustaining and self-regulating ecological systems.

borehole. A hole bored or drilled into the earth to obtain geologic and hydrologic samples, to allow injection or extraction of materials, or for other purposes.

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. 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.

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

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

corrosion-allowance materials. Materials that fail by generalized corrosion and that tend to fail more rapidly than corrosion-resistant materials.

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

critical group. The group that is representative of the individuals in the population who, on the basis of cautious but reasonable assumptions, are at the highest risk from exposure to repository releases.

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 control.

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 tunnel. A small exploratory tunnel across the proposed repository for enabling scientists to get a preview of the geologic and hydrologic conditions.

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

engineered barrier. A constructed component of a disposal system designed to slow down or prevent the release of radionuclides from the underground facility. This term includes the waste form, the waste package, materials placed over and around the waste package, and barriers used to seal penetrations directed into and within the underground facility.

enhanced characterization of the repository block. 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. 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.

environmental issues. Issues covering the potential effects that site-characterization activities and development, operation, and closure of a repository could have on the environment, which includes air; water; soil; and biological, cultural, and socioeconomic resources at and downstream, in surface water or groundwater, or downwind of the site for thousands of years. Environmental issues also include reclamation and restoration after, or mitigation of effects of, site characterization and repository construction, operation, and closure.

expert elicitation. The formal process through which expert judgment is obtained.

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 of the site's suitability to host a geologic repository.

exhaust drift. A tunnel in the repository used for ventilation.

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.

flux. The rate at which groundwater flows through the earth. Flux is the volume of flow per unit area of earth perpendicular to the direction of flow.

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.

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

geochemistry. The 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.

geosphere. The solid part of the earth.

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

heat pipe. See **refluxing.**

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 Nuclear Regulatory Commission determines requires permanent isolation by disposal in a geologic repository.

hydrogeology (groundwater geology). 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.

infiltration flux. The rate at which water from precipitation enters the rock below the surface root zone. See **flux**.

interim storage. Storage of spent fuel or high-level waste with the intention and expectation that the waste will later be removed to a permanent repository.

license application. A document submitted to the 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.

main drift. The main north-south tunnel through the exploratory studies facility.

market-driven approach. An initiative of the DOE for obtaining from private contractors virtually all of the services for transporting spent fuel from power plants to a geologic repository or an interim storage facility.

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

multipurpose canister. A sealed metallic container holding spent nuclear fuel assemblies in a dry, inert environment and inserted into different outer containers for storage, transportation, and disposal.

Nevada Test Site (NTS). A geographic area in southern Nevada that is owned and operated by the DOE and devoted primarily to the underground testing of nuclear devices. Yucca Mountain is on its southwest boundary.

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 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 (PL 100-203). The legislation that amended the Nuclear Waste Policy Act to limit repository site characterization activities to Yucca Mountain, Nevada; to establish the Office of the Nuclear Waste Negotiator to seek a state or an Indian tribe willing to host a repository or monitored retrievable storage facility; to create the Nuclear Waste Technical Review Board; and to increase state and local government participation in the waste management program.

peer review. A documented critical review performed by those who are independent from individuals who performed the work but who have technical expertise that is at least equivalent to those who performed the original work.

percolation flux. As used by the Yucca Mountain project, flux of water moving through the location where a repository would be built at Yucca Mountain. See **flux.**

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.

performance confirmation. The tests, experiments, and analyses that are conducted to evaluate the accuracy and adequacy of the information used to determine with reasonable assurance that the performance objectives for the period after permanent closure will be met.

postclosure. The period of time after the closure of the repository.

preclosure. The time before the closure of the repository.

probabalistic seismic hazard analysis (PSHA). An analysis that estimates the probabilities of adverse earthquake effects. See **seismic hazard.**

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.

radioactivity. The spontaneous emission of radiation from the nucleus of an atom. Radioisotopes of elements lose particles and energy through radioactive decay.

radionuclide. An atomic nucleus that is radioactive.

radionuclide plume. The route followed by water containing radionuclides as it flows from beneath the repository to the accessible environment.

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

refluxing. Flowing back, especially of water that is vaporized near waste packages, migrates to cooler areas, condenses, and then flows back toward the waste packages; sometimes referred to as the formation of “heat pipes.”

repository. See **geologic repository**.

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

risk. Possibility of suffering harm or loss because of some event. The magnitude of the risk depends on both the probability of occurrence of an event and the consequences if the event occurs.

robust. The adjective used to describe a condition that is unlikely to change despite uncertainties.

saturated rock. Rock in which all of the connected interstices or voids are filled with water.

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

seismic hazard. The adverse effects of earthquakes; for example, fault displacement and vibratory ground motion (shaking).

seismicity (seismic activity). The worldwide, regional, or local distribution of earthquakes in space and time; a general term for the number of earthquakes in a unit of time.

sensitivity studies. Mathematical analyses to determine which component or attributes of a system most strongly influence overall system performance.

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**.

site suitability. A high probability that a site, along with the appropriate engineered barriers, can provide long-term waste isolation.

siting guidelines. The criteria for evaluating the suitability of a candidate repository site; in 10 CFR 960.

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.

sorption characteristics. The ability of rocks and minerals to bind, reversibly or irreversibly, radionuclides or other chemical species on their surfaces.

source term. The compositions and the kinds and amounts of radionuclides that make up the source of a potential release of radioactivity from the engineered barrier system to the host rock.

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.

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

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

thermal energy. Heat produced by the radioactive decay of waste.

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

thermal testing. Tests run to determine how the heat of spent fuel and high-level waste might affect the performance of a repository at Yucca Mountain.

thermal zone. The region of the repository where the temperature has been increased by the presence of spent fuel and high-level waste.

total system performance assessment (TSPA). Analyses undertaken by the DOE 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.

transportation and storage system. Equipment for the acceptance, transportation, and interim storage of spent nuclear fuel.

unsaturated zone. Geologic formations located above the regional groundwater table.

viability assessment (VA). A congressionally mandated report that the Secretary of Energy is to provide to the President and Congress by September 30, 1998, and that includes repository and waste package designs, a total system performance assessment, a license application plan, and estimates of repository cost and schedule.

volcanism. The process by which molten rock and its associated gases rise from within the earth and are extruded on the earth's surface and into the atmosphere.

waste acceptance. The processes necessary for the DOE to take title to and physical possession of spent nuclear fuel or high-level radioactive waste from owners and generators of the wastes.

waste containment and isolation. Separation of waste from the environment so that any radioactive material re-entering the environment will be kept within prescribed limits.

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, fillers, 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.

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