U.S. NUCLEAR WASTE
TECHNICAL REVIEW BOARD

Report to

The U.S. Congress

and

The Secretary of Energy

January 1, 2005, to February 28, 2006

All NWTRB reports are available at **www.nwtrb.gov**, the NWTRB Web site.

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

June 2006

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

The Honorable Ted Stevens
President Pro Tempore
United States Senate
Washington, D.C. 20510

The Honorable Samuel W. Bodman
Secretary
U.S. Department of Energy
Washington, D.C. 20585

Dear Speaker Hastert, Senator Stevens, and Secretary Bodman:

The U.S. Nuclear Waste Technical Review Board submits this *Report to The U.S. Congress and The Secretary of Energy* in accordance with provisions of the Nuclear Waste Policy Amendments Act of 1987, Public Law 100-203, which requires the Board to report its findings and recommendations to Congress and the Secretary of Energy at least two times each year.

Congress created the Board to evaluate the technical and scientific validity of activities undertaken by the Secretary of Energy related to implementing the Nuclear Waste Policy Act of 1982. In this report, which covers the period of January 1, 2005, through February 28, 2006, the Board's major activities are summarized and the Board's technical evaluation of Department of Energy (DOE) work related to disposing of, packaging, and transporting spent nuclear fuel and high-level radioactive waste is presented.

The technical evaluation contained in the report focuses on six important technical issues: (1) the capability of natural barriers at Yucca Mountain to isolate radionuclides; (2) the DOE's thermal-management strategy; (3) the range of potential near-field environments and their possible effects on the engineered barrier system; (4) postclosure risk associated with the repository; (5) design and operation of surface and subsurface components and facilities; and (6) DOE plans for the waste-management system.

In the appendices to the report are Board correspondence, congressional testimony, Board performance plans and evaluations, and related materials.

The Board hopes that the information in the report will provide a useful technical context as important decisions are made on managing the nation's spent nuclear fuel and high-level radioactive waste.

Sincerely,

B. John Garrick
Chairman

Nuclear Waste Technical Review Board 2005

Dr. B. John Garrick, Chairman
Consultant
Newport Beach, California

Dr. Mark D. Abkowitz
Vanderbilt University
Nashville, Tennessee

Dr. Wm. Howard Arnold
Consultant
Macatawa, Michigan

Dr. Daryle H. Busch[1]
University of Kansas
Lawrence, Kansas

Dr. Thure E. Cerling
University of Utah
Salt Lake City, Utah

Dr. David J. Duquette
Rensselaer Polytechnic Institute
Troy, New York

Dr. George M. Hornberger
University of Virginia
Charlottesville, Virginia

Dr. Andrew C. Kadak
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dr. Ronald M. Latanision
Exponent Corporation
Natick, Massachusetts

Dr. Ali Mosleh
University of Maryland
College Park, Maryland

Dr. Henry R. Petroski
Duke University
Durham, North Carolina

[1] Resigned July 15, 2005

Executive Staff

William D. Barnard	*Executive Director*
Joyce M. Dory	*Director of Administration*

Technical Staff

Carlos A. W. DiBella	*Senior Professional Staff*
David M. Diodato	*Senior Professional Staff*
Daniel J. Fehringer	*Senior Professional Staff*
Daniel S. Metlay	*Senior Professional Staff*
John H. Pye	*Senior Professional Staff*
Leon Reiter	*Senior Professional Staff*

External Affairs Staff

Karyn D. Severson	*Director*
Paula N. Alford	*International Programs*

Information Technology Staff

William D. Harrison	*Systems Administrator*
Davonya S. Barnes	*Information Systems Specialist*

Administrative & Support Staff

Linda Coultry	*Program Management Specialist*
Alvina Hayes	*Administrative Assistant*
Linda L. Hiatt	*Management Analyst*
Victoria F. Reich	*Librarian*

Table of Contents

Executive Summary

The U.S. Nuclear Waste Technical Review Board (Board) was established by Congress in the Nuclear Waste Policy Amendments Act. The Act requires the Board to evaluate the technical and scientific validity of the work undertaken by the U.S. Department of Energy's (DOE) Yucca Mountain Project (Project) to develop a geologic repository system for disposing of spent nuclear fuel and high-level radioactive waste produced by the nation's nuclear defense complex and commercial nuclear power plants. The results of the Board's evaluation, along with its recommendations, must be reported at least twice yearly to Congress and to the Secretary of Energy. Between January 1, 2005, and February 28, 2006, the period covered by this report, the Board focused its evaluation on six critical technical issues. In what follows below, the Board's major findings and recommendations for each of the six areas are presented.

A. The Capability of Natural Barriers to Isolate Radionuclides

Two potentially significant natural barriers at Yucca Mountain—the unsaturated zone beneath the repository horizon and the saturated zone—can isolate radionuclides that might be released from the emplaced waste packages. The Board believes that the Project has made great strides over the last few years in developing a sound understanding of the magnitude and rates of mountain-scale groundwater flow in the unsaturated and saturated zones under ambient temperatures and current climatic conditions. Although the Project should continue to evaluate new data as they become available and refine its conceptual models as warranted, new understanding is likely to emerge in an evolutionary rather than a revolutionary manner. The Board believes, however, that additional work is needed on processes and phenomena that could significantly affect the rate at which dose-significant radionuclides are transported. Such work should include investigations into matrix diffusion, secondary mineralization, and colloid-facilitated transport.

B. Thermal-Management Strategy

A key driver in the performance of the repository, both preclosure and postclosure, is temperature. The temperature of the spent nuclear fuel affects the integrity of the fuel cladding and the susceptibility of the waste-package material to localized or general corrosion. The temperature and time profiles in the near-field environment of the drift affect tunnel degradation, causing more fracture pathways, drift separation, and movement of water or water vapor in the unsaturated zone. How these temperatures are controlled is determined by the Project's thermal-management strategy, which identifies controlling criteria, including the maximum thermal loading of the waste packages, line loading in the emplacement drift, and peak temperatures and zones for pillar separation.

The Board has concerns about the technical basis underlying the Project's thermal-management strategy. First, the technical basis for the Project's choice of thermal criteria to limit temperature is not well-defined. The Board believes that the Project should articulate in a transparent way the basis for its thermal criteria. Second, the implications for thermal management of the Project's provisional decision to develop and implement a standardized canister for storing, transporting, and disposing of spent nuclear fuel do not seem to have been evaluated fully. The Board is particularly concerned about the ability of the utilities to blend the spent nuclear fuel to the required thermal loading, given the spent nuclear fuel available in the spent-fuel pools, the increasing volume of spent nuclear fuel in dry storage at reactors, and the trend toward higher burn-up fuel. Moreover, the Board is concerned that the constraints imposed by line-load requirements during emplacement have not been fully represented or understood in terms of surface facility design and operation. Third, the Board is not persuaded that the thermal-hydrologic models being used to predict postclosure temperature, relative humidity, and vapor transport within the drifts have a strong technical basis.

C. The Range of Possible Near-Field Environments that Might Occur and the Effect of Those Environments on the Integrity of the Engineered Barrier System

The engineered barrier system consists of the spent nuclear fuel, including the cladding and the fuel pellets; the waste package, including any canister or basket holding the spent nuclear fuel or high-level radioactive waste; the waste package invert; the drip shield; and the backfill, if any. As do the natural barriers, the engineered barrier system can contribute to waste isolation.

The Alloy-22 outer barrier of the waste package will not corrode significantly unless liquid water is present on the waste package surface. The higher the temperature at which liquid water is present, the greater is the concern, because metals generally corrode faster at higher temperatures and the susceptibility of metals to corrosion generally increases at higher temperatures. Project scientists have determined that dusts from ventilation air during the preclosure period would settle on waste package surfaces and would contain salts that could form saturated brines with boiling points on the order of 200ºC.

The Project maintains that potential localized corrosion of Alloy-22 at elevated temperatures can be excluded from its performance-assessment calculations. The Board believes that the technical basis for the exclusion is not compelling, partly because only very limited corrosion data have been collected at temperatures above 150ºC and partly because data showing cessation (stifling) of localized corrosion at lower temperatures may or may not be relevant to all conditions under which localized corrosion could occur in the proposed repository. The Board strongly urges the Project to continue collecting data that might justify its assumption that localized corrosion will not occur at temperatures as high as 200°C.

D. The Postclosure Risk Associated with the Proposed Repository

Beginning in 1991, the Project carried out seven performance assessments for the proposed repository at Yucca Mountain, and it is preparing an eighth assessment, which it intends to use for supporting its application for a license to construct the repository.

The Board appreciates the fact that the Project is in the midst of preparing a license application for its proposed repository system. Not surprisingly, the Project is motivated to advance a licensing case whose main—and possibly sole—objective is to demonstrate compliance with the applicable regulations via an intensely legalistic process. Consequently, when faced with gaps in understanding, “bounding” or conservative approaches are often adopted. What is difficult to assess is the degree of total conservatism that exists when scientists add their own conservatism in the chain of integrated analyses that form the performance assessment.

For that reason, the Board remains concerned that by adopting a conservative compliance-focused approach, the Project discounts the importance of letting policy-makers, the public, and the broader technical and scientific community know what the Project’s experts believe are the intrinsic capabilities of the proposed repository at Yucca Mountain. Having more-definitive information on the adequacy of the natural system and the levels of conservatism involved, for example, may well provide all interested and affected parties with important and relevant information.

Thus, the Board believes that the Project should carry out a realistic performance assessment, perhaps in parallel with its efforts to develop a compliance case. Such a realistic performance assessment would establish a "baseline" for measuring how "conservative" or "nonconservative" the Project's licensing case might be. Although some assumptions still may be required, they, too, will need to be well justified if this realistic assessment is to be carried out credibly. Thus the Board reiterates its view that fundamental understanding is important and encourages the Project to fill in areas where significant gaps in such understanding exist.

Further, to address what now appear to be the critical radionuclides contributing to peak dose, the Board recommends that the Project prepare full and realistic process models that account for the transport of the two radionuclides in question, neptunium-237 and plutonium-242. Such an effort should trace the radionuclides from when they leave the degraded fuel pellet until they are taken up by the "reasonably maximally exposed individual." These analyses should be consistent with the thermal hydraulic analyses used in the thermal-management strategy. The model calculations should extend until the time of peak dose or 1,000,000 years.

E. Design and Operation of Surface and Subsurface Components and Facilities

In recent years, the Project has intensified its efforts to design and develop concepts-of-operation for the surface and subsurface facilities that might be constructed at Yucca Mountain. The Board looks favorably on the Project's provisional decision to implement the standardized transportation-aging-disposal canister concept. It believes that such an approach holds the potential for minimizing the handling of bare fuel assemblies, for simplifying the design of surface facilities, and for reducing occupational exposures. As noted above in the thermal-management discussion, the Board remains concerned that the Project has not fully evaluated the range of consequences associated with implementation of the standardized transportation-aging-disposal canister concept. The Board recommends that the Project carry out a comprehensive formal analysis that would better specify the full effect of adopting the standardized transportation-aging-disposal canister concept. Such an analysis should take into consideration a full complement of scenarios that can evaluate various design and operational assumptions associated with waste acceptance, transport, receipt and processing at the surface facilities, and emplacement.

F. Plans for the Waste-Management System

The waste-management system consists of elements that collectively must carry out a range of functions: accepting waste at a utility or, if needed, at DOE defense-complex sites; handling, transporting, processing, and storing the waste; and, finally, emplacing the waste underground. Because the elements of the waste-management system are tightly coupled, the assessment of the behavior and performance of one element may strongly depend on or affect the behavior and performance of others.

The Board notes that the Project has begun development of the Total System Model, which has significant potential as a tool for understanding the performance of the coupled waste-management system. The Total System Model, for example, can be used to examine system throughput, identify possible "choke" points, and show where various design and operational elements are incompatible. For maximizing the value of the Total System Model, however, the input data must be based on the most up-to-date information; critical modeling assumptions also must be confirmed; there should be an ability to represent upset conditions; and all components of the waste-management system, including emplacement, need to be incorporated in the model. The Board recommends, therefore, that these enhancements be pursued actively. The Board further recommends that the Total System Model be used by designers of the surface facilities and all other components of the waste-management system to determine needs and capabilities and to eliminate problems or constraints in the future.

Because of funding constraints, much of the Project's anticipated work on establishing a transportation network has been deferred. Nonetheless, the Board believes that the Project should move expeditiously to perform a comparative risk analysis of alternative rail corridors that might be used to move spent nuclear fuel and high-level radioactive waste to Yucca Mountain. Once that risk analysis has been completed, the DOE should inform all interested and affected parties what route(s) it prefers. In addition, the Project should develop a contingency plan for greater use of legal-weight and heavy-haul trucking.

Board Activities

The U.S. Nuclear Waste Technical Review Board (Board) was established by Congress in the Nuclear Waste Policy Amendments Act (NWPAA) (U.S. Congress 1987). The Act requires the Board to evaluate the technical and scientific validity of the work undertaken by the U.S. Department of Energy's (DOE) Yucca Mountain Project (Project) to develop a geologic repository system for disposing of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) produced by the nation's nuclear defense complex and commercial nuclear power plants. The results of the Board's evaluation, along with its recommendations, must be reported at least twice yearly to Congress and the Secretary of Energy. This document is the first such report for 2006.

Between January 1, 2005, and February 28, 2006, the period covered by this report, the Board focused its attention on the Project's efforts to develop post-closure performance estimates for the repository it proposes to construct at Yucca Mountain in Nevada. The Board considered areas where the Project could improve its understanding of the capability of the natural system, the unsaturated and saturated zones in particular, to isolate the radionuclides of the SNF and HLW. The Board continued its evaluation of how the waste packages might perform if they were emplaced in the proposed repository. Finally, the Board also examined the Project's planned waste-management system that is needed to accept, transport, and handle SNF and HLW before their disposal.

The Board's mandate to review the DOE's waste disposal project is broad, encompassing the technical and scientific aspects of all of the Secretary of Energy's actions to implement the NWPAA. During the period covered by this report, the Board continued evaluating the work that the Project is pursuing to prepare a license application (LA) for constructing the proposed repository. The LA contains, among other things, a Total System Performance Assessment (TSPA), which details the Project's technical case for how a Yucca Mountain repository might isolate SNF and HLW for many tens of thousands of years, the so-called postclosure period. The LA also contains the DOE's Preclosure Safety Analysis, which is intended to demonstrate how the performance requirements for the operational phase of the proposed repository will be met. Once completed and submitted, the LA eventually will be the subject of a U.S. Nuclear Regulatory Commission (NRC) adjudicatory hearing and determination.

At the same time, the Board continued its longstanding tradition of encouraging the Project to undertake investigations and analyses that go beyond licensing requirements so that there is greater transparency in the fundamental processes involved and to increase public confidence in the conclusions reached in the TSPA. The Board's position is that the Project's conclusions about postclosure repository performance need to be compelling, convincing, and strongly evidence-based. This position traces to the Board's beginnings. It was formally articulated in comments that the Board made, first in 1997 and again in 2000, on two Project proposals for revising its original site-suitability guidelines (Cohon 1997, 2000). Further, the Board suggested that the Project seek out multiple lines of evidence about repository performance, such as natural or engineered analogues, that are independent of the TSPA (NWTRB 2001). On several occasions, the Board also noted the importance of increasing "fundamental understanding" to reduce the uncertainties associated with the TSPA. (See, for example, Cohon 2002.) Most recently, the Board recommended that the Project conduct a "more realistic" TSPA (Garrick 2005c, 2006).

I. Events Influencing the Board's Review

As President George W. Bush's second term began in 2005, significant changes took place in the senior leadership of the Office of Civilian Radioactive Waste Management (OCRWM), which has responsibility for the Project. A new Acting Director initiated a review of the full range of activities taking place within the office. That review ultimately led to two important programmatic shifts and initiated a significant reorganization.

- The OCRWM instructed its lead contractor, Bechtel-SAIC Corporation (BSC), to devise a plan for operating the Yucca Mountain repository as a primarily "clean" or non-contaminated facility. The change in surface facility design meant that most SNF would be sent to the repository in a standardized transport-aging-disposal (TAD) canister that would not require repetitive handling of bare SNF before its disposal. Earlier plans called for shipping SNF in various types of canisters to the repository where workers would handle each of the bare SNF assemblies up to four times.

- The OCRWM designated Sandia National Laboratories (SNL) as its lead laboratory for integrating the Project's scientific work related to the evaluation of repository performance during the postclosure period. As the OCRWM's lead laboratory, SNL would provide management and integration services for all Yucca Mountain scientific programs, a task previously assigned to BSC.

- The OCRWM began restructuring itself to create a flatter organization. The heads of 13 offices will be expected to report directly to the Director/Principal Deputy Director, located in Washington D.C. The former distinction between "east" and "west" will be eliminated; within any given office, people can work either in Washington or in Las Vegas.

In March 2005, Secretary of Energy Samuel W. Bodman announced that "certain employees of the U.S. Geological Survey (USGS) working on the Yucca Mountain project may have falsified documentation of their work." The documentation in question related to computer modeling involving water infiltration and climate (DOE Office of Public Affairs 2005). Separate investigations of this matter were launched by the OCRWM, and the Inspectors General of the Departments of Energy and Interior. In February 2006, the OCRWM released a report detailing the results of its investigation (OCRWM 2006). The OCRWM maintained that the net infiltration ranges developed by the USGS were "consistent with groundwater recharge rates determined by other scientists studying other arid and semi-arid regions in the United States." Notwithstanding this conclusion, the OCRWM said that it will "replace or supplement the infiltration modeling work, as needed, and will review or verify the supporting documentation…" (DOE Office of Public Affairs 2006).

In August 2005, the U.S. Environmental Protection Agency (EPA) proposed changes to its Yucca Mountain-specific environmental standard (EPA 2005). The EPA's proposal responded to a July 2004 Court of Appeals decision *(Nuclear Energy Institute v. EPA)* that had vacated the 10,000-year compliance period in the previously promulgated standard, 40CFR197. In particular, the EPA requested public comments on the following changes to its standard:

- The compliance period should extend to the time of peak dose but for no more than 1,000,000 years.

- For the first 10,000 years, the individual protection standard should be 15 mrem/year. For the remainder of the compliance period, the individual protection standard should be 350 mrem/year.

- The figure of merit for judging compliance during the first 10,000 years should be the mean of the projected dose rates. For the remainder of the compliance period, the figure of merit should be the median of the projected dose rates.

- Features, events, and processes (FEP's) that have an annual probability of occurrence that is greater than 10^{-8}/year must be included in the TSPA. FEP's not satisfying that probability criterion during the first 10,000 years also may be excluded in the performance assessment that is carried out for the remainder of the compliance period. However, four FEP's and their associated scenarios—climate change, seismic events, volcanic events, and general corrosion—must be included in the 1,000,000-year/peak-dose TSPA regardless of their annual probability of occurrence.

Shortly thereafter, the NRC proposed modifications to its licensing regulation, 10CFR63, so that its rule would conform to the changes that the EPA proposed and to specify how climate should be modeled during the post-10,000-year part of the compliance period (NRC 2005).

In February 2006, as part of its Advanced Energy Initiative, the Administration requested $250 million to launch the Global Nuclear Energy Partnership (GNEP). In the Administration's vision, if fully implemented over the next several decades, the GNEP would foster the building of a new generation of nuclear power plants, would develop and deploy new nuclear recycling technologies, would design Advanced Burner Reactors to produce energy from the recycled nuclear fuel, and would provide fuel services to developing nations to reduce the risks of nuclear proliferation. The DOE has emphasized in statements to Congress and elsewhere that a Yucca Mountain repository would still be necessary even if the GNEP is implemented fully. In those statements, the DOE has maintained that one important consequence of a fully implemented GNEP would be to increase substantially the capacity of the proposed Yucca Mountain repository. At this time, it is unclear what the prospects are for approval by Congress of this or subsequent budget requests or what GNEP's ultimate impact on the Yucca Mountain repository project might be.

II. Board Review of the OCRWM's Technical and Scientific Investigations

Early in 2005, the Board developed a set of critical technical issues that it believed warranted its special attention. These priority issues, announced at the Board's November 2005, meeting, include the following:

- The capability of natural barriers to isolate radionuclides;

- Thermal-management strategy;

- The range of possible near-field environments that might occur and the effect of those environments on the integrity of the engineered barrier system (EBS);

- The postclosure risk associated with the proposed repository;

- Design and operation of surface and subsurface components and facilities;

- Plans for the preclosure waste-management system, including transportation; and

- A comparison of preclosure and postclosure human exposure to radiation.

Once these priorities were established, it became very clear that the Board needed to interact with the Project in a concerted manner that permitted in-depth technical exploration of the issues. Toward that end, small contingents of Board members and staff held eight fact-finding meetings with the DOE and its contractors between March and September of 2005. As they are obligated to do under the NWPAA, Project scientists and engineers presented a number of ongoing scientific investigations and analyses, many of which contained preliminary results still in draft form. These fact-finding meetings were productive and enabled the Board to engage in the detailed and lengthy technical discussions that are necessary to understand many of the fundamental methods of analysis employed by the Project. In addition to the meetings with the Project, several Board members and staff held separate talks with representatives of railroads, trucking companies, cask manufacturers, transportation logistics providers, and nuclear utilities. The purpose of these meetings was to gather first-hand information from key stakeholders who would be involved in designing and operating the waste-management system. Importantly, all of these fact-finding meetings were undertaken in part to improve the technical substance and relevance of the Board's public meetings.

The Board, in fact, was able to explore all but the last of its priority issues at its public meetings. In what follows, the OCRWM's technical and scientific investigations with respect to each issue, as articulated at those meetings, are described, and the Board's findings and recommendations are presented.

A. The Capability of Natural Barriers to Isolate Radionuclides

Two potentially significant natural barriers at Yucca Mountain—the unsaturated zone beneath the repository horizon and the saturated zone—can isolate radionuclides that might be released from the emplaced waste packages.

1. The OCRWM's Technical and Scientific Investigations

Unsaturated zone. The ability of the unsaturated zone to isolate radionuclides under ambient conditions depends on, among other things, the amount of liquid water that flows through it, the chemical form and solubility of the radionuclides released from the EBS, the path the water takes through the rock, and the ability of the rock to retard or retain the radionuclides mechanically or chemically.

The amount of water flowing in Yucca Mountain is determined in the first instance by climate, which affects the amount of rain and snowfall. A fraction of that water infiltrates beneath the root zone and percolates down into the rock. The topographic and geologic variability of Yucca Mountain results in some areas having relatively enhanced infiltration and other areas having relatively reduced infiltration. The belief is that water percolating down is diverted around repository drifts by physical forces rather than seeping into them. Estimating how much water is likely to be available to transport radionuclides outside the proposed repository is a key objective of the Project.

At the Board's February 9, 2005, meeting (NWTRB 2005a), one Project scientist presented preliminary data on opal growth rates over the last several hundred thousand years (Andrews 2005). According to the scientist, such growth rates depend on how much water passes through the unsaturated zone at the proposed repository horizon. Although not conclusive, these data suggested to the presenter that the repository level at Yucca Mountain is buffered from long-term transient climate states. At the Board's February 1, 2006, meeting (NWTRB 2006), another Project scientist described the approach taken in the TSPA to modeling the seepage of liquid water entering the drifts (Birkholzer 2006). In addition, new calculations not used in the current TSPA analysis indicate that water vapor present in the drifts could condense on the drip shields and waste packages (Hardin 2006). In-drift condensation occurs because a temperature gradient develops along the axis of the emplacement drift that is caused by the relatively hot waste packages at the center and cooler waste packages at the edge of a repository. This condensation phenomena typically is referred to as the "cold-trap" effect.

Once water enters the drifts either by seepage or by condensation, it is available to dissolve and transport any radionuclide released from the waste packages. Radionuclides could be transported as dissolved species, as either sorbed reversibly or irreversibly on to colloids, or as true colloids. Two radionuclides, neptunium-237 (^{237}Np) and plutonium-242 (^{242}Pu), are particularly important in the projections of repository performance carried out to the time of peak dose or 1,000,000 years. Project scientists reported at the Board's February 1, 2006, meeting, that the Project had undertaken investigations and analyses to understand better the chemistry, solubility, and genesis from SNF degradation of the likely oxide forms of the those two radionuclides (Sassani and Howard 2006a). As a result of those studies, the Project concluded that the solubility of the neptunium isotope was best modeled by a reduced form (NpO_2) inside the waste package and by a more oxidized form (Np_2O_5) outside the waste package. In the models, the plutonium isotope is transported primarily by reversible and irreversible attachment to colloids. Work is being carried out to estimate the relevant rate constants (Sassani and Howard 2006b). Finally, investigations are ongoing to learn more about how neptunium and plutonium bond chemically with the products of SNF degradation and waste package corrosion.

The current conceptual model holds that fluid flow and advective radionuclide transport in the unsaturated zone takes place mostly through fractures. The model recognizes that diffusion into the rock matrix also is a significant radionuclide transport process. Some Project studies suggest that the magnitude of matrix diffusion for relevant scales in nature may be greater than is currently represented in Project computer models, which are based on laboratory-scale data. Underestimation of the magnitude of matrix diffusion in computer models would underestimate the amount of time required for radionuclides that diffuse into the rock matrix to be transported through the actual hydrogeologic system, resulting in earlier, larger dose projections.

Saturated zone. The saturated zone receives all of the water draining from the unsaturated zone and any radionuclides in that water. At Yucca Mountain, the rocks of the saturated zone are predominantly volcanic tuffs and alluvial sediment. The capability of the saturated zone to isolate radionuclides depends on, among other things, the form and quantity of the radionuclides, climate, the physical and chemical properties of the rock, the magnitude of matrix diffusion, water-flow rates and water chemistry, especially oxidation state, and the amount of sorption onto rock and mineral surfaces. As the Project's understanding of each of these variables matures, its estimates of the capability of the saturated zone could become less uncertain.

At the Board's February 1, 2006, meeting, a Project scientist described how water flow and radionuclide transport are modeled in the TSPA (Arnold 2006). Climate change is represented by scaling the computed time required for radionuclides to reach the accessible boundary, a point approximately 18 km south of the proposed repository footprint, in proportion to flux changes in the saturated zone. Matrix-diffusion calculations in the saturated zone depend on the spacing between flowing horizons in the rock, the magnitude of rock porosity, and the diffusion coefficient for the radionuclide. The scientist described the uncertainties associated with estimates of each of these variables. In particular, he noted that, as in the unsaturated zone, the effect of matrix diffusion in the saturated zone might be underestimated in the Project's models.

The sorption conceptual model also was described. It incorporated unique sorption characteristics for each radionuclide and rock substrate. Here again, the modeling had to address uncertainties, such as sorption coefficients for the tuff matrix and alluvium, dispersivity, effective porosity of the alluvium, colloid retention factor, and sorption coefficients onto colloids. As a result of a combination of natural variability and model uncertainty, the saturated zone breakthrough curves for neptunium ranged from 30 years to more than 20,000 years. The Project scientist stated that the sorption modeling presumed that the groundwater was oxidizing. He noted, however, that there were some indications that local reducing conditions may exist in the saturated zone. Reducing conditions would decrease the solubility and increase the sorption coefficients of technetium and neptunium. In his view, such changes would increase the capability of the saturated zone to isolate radionuclides.

2. Board Findings and Recommendations

The Board believes that the Project has made great strides over the last few years in developing a sound understanding of the magnitude and rates of mountain-scale groundwater flow in the unsaturated and saturated zones under ambient temperatures and current climate conditions. Further, the Board considers the Project's findings regarding the chemistry of the water in the unsaturated and saturated zones under ambient conditions broadly consistent with a large body of empirical data and experience. Although the Project should continue to evaluate new data as they become available and refine its conceptual models as warranted, new understanding is likely to emerge in an evolutionary rather than a revolutionary manner.

The Board believes, however, that additional work on radionuclide transport is needed—in particular, research on secondary mineralization (Garrick 2005c). This area of investigation relates to what is more generally referred to as the radionuclide source term, the understanding of which is critical to assessing the overall performance of the proposed repository. If these investigations determine that the neptunium and plutonium leaving the EBS are captured in secondary mineral phases, the possibility exists that the natural system's capability to isolate the dose-contributing radionuclides (^{237}Np and ^{242}Pu) could be greatly increased. Further work investigating matrix diffusion, colloid-facilitated transport, or other processes that might significantly affect the rate at which dose-significant radionuclides are transported also could yield important insights. In addition, the Peña Blanca analogue site in Mexico provides an opportunity to test models and methods for predicting radionuclide migration and retention processes at Yucca Mountain. The Board encourages the Project to continue studies at that location. In short, the Board believes that it would be prudent for the Project to refine its understanding of radionuclide retardation and retention phenomena to evaluate better the potential contribution that the natural system might make to isolating radioactive waste.

The Board is skeptical about the Project's claim to have found evidence of a "reducing curtain" in the saturated zone. Once oxidized water flows into a reducing zone (and becomes reduced), it cannot simply flow out "the other side" and become reoxidized. Thus the Project's conjecture that localized reducing conditions might retard some radionuclides does not seem well founded unless the entire groundwater flow path is reducing. There does not appear to be evidence to support such a claim.

Finally, the Board remains puzzled about the Project's inability to put to rest two longstanding issues: whether bomb-pulse chlorine-36 (^{36}Cl) has been observed at the proposed repository horizon and whether the water found behind the sealed section of the cross-drift is the result of condensation or seepage. (Neither issue was mentioned in any of the Project's presentations at the three public meetings.) Inconsistencies in past studies of ^{36}Cl, for example, raise questions about the technical basis of model predictions of water flow and radionuclide transport. In the case of the water found in the sealed section of the cross-drift, the Project has not developed and tested a hypothesis that explains all of the physical and chemical data collected. To enhance confidence in both the quality and the conclusions of the Project's technical analyses, the Board recommends that work be expedited to resolve both of these issues.

B. Thermal-Management Strategy

A key driver in the performance of the repository, both preclosure and postclosure, is temperature. Temperatures of interest include the temperature of the SNF and HLW at the time of emplacement, the temperature on the waste package wall, the drift wall temperature, and the near-field drift temperatures. The temperature of the SNF affects the integrity of the fuel cladding (a barrier) and the susceptibility of the waste-package material to localized or general corrosion. The temperature and time profiles in the near-field environment of the drift affect tunnel degradation, causing more fracture pathways, drift separation, and movement of water or water vapor in the unsaturated zone.

The Project's thermal-management strategy is comprised of three elements (Harrington 2005): (1) development of thermal criteria that constrain the size, age, and contents of waste packages; this in turn limits how hot the waste packages can be and how that heat will be distributed among the thousands of packages emplaced in the drifts of the proposed repository; (2) how those thermal criteria will be achieved during preclosure operations involving waste acceptance and handling, blending, staging and sequencing of the waste packages during emplacement; and (3) how the emplaced waste packages influence critical variables during the thermal pulse that relate to the near-field environment, including drift-wall temperature, seepage, in-drift transport of water vapor, chemistry, and radionuclide transport. Clearly then, the thermal-management strategy creates the most important bridge between preclosure activities and postclosure performance.

1. The OCRWM's Technical and Scientific Investigations

At the Board's February 9, 2005, meeting, an engineer described the Project's thermal-management strategy (Harrington 2005). He stated that during preclosure surface operations the key thermal criterion was keeping the SNF below 400°C to maintain cladding integrity. Once the waste packages are emplaced in the proposed repository, their surface temperatures cannot exceed 300°C. Cladding temperature of the SNF cannot exceed 350°C once the SNF is emplaced and throughout the postclosure period. The Project also has established the following criteria: (1) The waste package thermal power cannot be greater than 11.8kW; (2) The packages would have to be emplaced so that they would not heat the drift wall to a temperature higher than 200°C or heat the center part of the drift rock pillar to more than 96°C; (3) The maximum average thermal line load cannot exceed 1.45 kW/meter.

According to this individual, several options are available to ensure that these thermal criteria can be satisfied.

- Waste packages can be derated, i.e., not fully loaded.
- Hot SNF can be blended in the same waste package with cooler SNF.
- The packages can be spaced farther apart than the baseline design now specifies.
- The proposed repository can be ventilated for longer than the time now called for in the baseline design.
- Waste packages can be stored on the surface until they have cooled.

The Project engineer gave no indication that satisfying either the preclosure or postclosure thermal criteria would be difficult. He noted, for example, that the Project intends to construct concrete pads that would have enough room to accommodate up to 21,000 MTHM of stored SNF, or approximately 30 percent of the amount of waste allowed to be disposed of at Yucca Mountain under current law.

At one of the fact-finding meetings, officials from the Project discussed in greater detail the technical basis that supported the choice of the thermal criteria. The Board members explored how those choices constrained the design of the repository. They also reviewed the Project's efforts to model seepage into the drifts, water-vapor transport within the drifts, and condensation of water vapor in the pillars separating the drifts.

2. Board Findings and Recommendations

The Board has concerns about the technical basis underlying the Project's thermal-management strategy. These concerns manifest themselves in each of the three elements that constitute the strategy. First, the technical basis for the Project's choice of thermal criteria to limit temperature is not well-defined. For example, the 11.8 kW/waste package limit appears to have been based arbitrarily on the average power of a PWR SNF assembly plus 20 percent. A more technically valid approach might be to derive the maximum waste package-surface temperature limit from limits on the drift-wall temperature. A limit derived from the drift-wall temperature would likely be higher than 11.8 kW/waste package, although how much higher still is not well understood. The Board believes that the Project should articulate in a transparent way the basis for its thermal criteria. The Board will be holding future fact-finding meetings to evaluate further the technical basis for the Project's proposed thermal criteria.

Second, the implications for thermal management of the Project's provisional decision to implement the TAD concept do not seem to have been evaluated fully. In particular, the Board is concerned about the ability of the utilities to blend the SNF to the required thermal loading, given the SNF available in the spent-fuel pools, the increasing volume of SNF in dry storage at reactors, and the trend toward higher burn-up fuel. For example, assuming an 11.8 kW/waste package limit, how long would a waste package have to be stored at Yucca Mountain if its initial thermal output was substantially higher than this limit? Utilities are storing SNF at their sites in dry storage casks. This SNF is predominantly older, cooler material, which may not be available for future TAD packages. The longer the delay in implementing the TAD concept, the more SNF will be placed in storage casks. Those casks might have to be reopened at the proposed repository, thereby negating at least some of the value of the TAD concept. Moreover, the Board is concerned that the constraints imposed by line-load requirements during emplacement have not been fully represented or understood in terms of surface facility design and operation. The Board looks forward to reviewing the Project's assessment of the full range of consequences associated with implementing the TAD concept.

Third, the Board is not persuaded that the thermal-hydrological models being used to predict postclosure temperature, relative humidity, and vapor transport within the drifts have a strong technical basis. For example, the thermal conductivity of the rock at Yucca Mountain is important for predicting thermohydrologic conditions in the proposed repository. Uncertainty in the thermohydrologic conditions, especially during the thermal pulse that lasts about 1500 years, arises in part from the scarcity of *in situ* measurements of thermal conductivity in the lower lithophysal rocks where approximately three-quarters of the repository might be constructed. More data on thermal conductivity could reduce this uncertainty (Garrick 2005c). In addition, further analysis of data obtained from the Drift-Scale Heater Test might be helpful in reducing the uncertainty in thermohydrologic conditions during the thermal pulse.

Finally, the Project is conducting three-dimensional analyses to complement its two-dimensional multiscale model of water and vapor flow. The Board plans to review those new analyses to determine what impact, if any, they might have on the Project's safety case. In particular, the Board would like to see how energy and mass balances are achieved and how these results are integrated into performance assessment. Due to the importance of the multiscale model, the Board also recommends that it be reviewed by independent experts.

C. The Range of Possible Near-Field Environments that Might Occur and the Effect of Those Environments on the Integrity of the EBS

The EBS consists of the SNF, including the cladding and the fuel pellets; the waste package, including any canister or basket holding the SNF or HLW; the waste package invert; the drip shield; and the backfill, if any. As do the natural barriers, the EBS can contribute to waste isolation.

1. The OCRWM's Technical and Scientific Investigations

Waste package. For the last few years, the Board has explored whether localized corrosion of the Alloy-22 waste package might occur at temperatures higher than 150ºC by the action of concentrated deliquescent brines (Corradini 2003a, 2003b; NWTRB 2003). After a public meeting held in May 2004 (NWTRB 2004b), the Board concluded that deliquescence-induced localized corrosion due to calcium chloride brines during the higher-temperature period of the thermal pulse would be unlikely because of the improbability of such brines being present (Duquette 2004). Because no other plausible brines were known to exist at temperatures above 150ºC, the issue of localized corrosion above 150ºC due to concentrated deliquescent brines seemed to be closed. A January 2005 letter to the Board from former OCRWM Director Margaret Chu, however, reopened the issue (Chu 2005). The letter suggested that *combinations of salts* known to be present in the drifts at Yucca Mountain could deliquesce at temperatures as high as 200ºC. One question that remained to be answered was whether this combination of salts might cause localized corrosion.

After considerable investigation and analysis, the Project concluded that localized corrosion was so inconsequential that it could be excluded from the list of FEP's that needed to be evaluated in the TSPA. In a pair of presentations at the Board's November 8, 2005, meeting (NWTRB 2005b), Project scientists laid out the technical arguments that led to that conclusion (Bryan 2005; Ilevbare 2005). The presentations sought to address the following logic tree:

1. Can multiple-salt-deliquescent brines form at elevated temperatures?
2. If deliquescent brines form at an elevated temperature, will they persist?
3. If deliquescent brines persist, will they be corrosive?
4. If potentially corrosive brines were to form, would they initiate localized corrosion?
5. If localized corrosion were to be initiated, would penetration of the waste-package outer barrier occur?

One scientist stated that, according to experimental data, a mixture of $NaCl–KNO_3–NaNO_3$ could deliquesce at temperatures up to approximately 200ºC at the relative humidities that will exist in a repository at Yucca Mountain at that temperature. Thus, the answer to the first question is "yes." Moreover, the monovalent salt brines will not degas sufficiently to dry out at elevated temperatures. Consequently, the answer to the second question also is "yes."

The scientist maintained that the answer to the third question is "no," at least for temperatures below 160ºC. The deliquescent brines studied, both initially and after interacting with the waste package surface, possess a high nitrate-to-chloride ratio. Experimental evidence obtained at temperatures as high as 160ºC indicate that nitrate-rich brines do not initiate localized corrosion. However, some new data at higher temperatures showed localized corrosion on creviced Alloy-22 samples. These data are still being evaluated. Depending on that evaluation, the Project may have to adjust its position on the corrosivity of $NaCl–KNO_3–NaNO_3$ brines at high temperatures.

Regardless of the corrosivity of the brine, the second scientist argued that the answer to the fourth question also is "no." The Project calculated an upper limit to the brine volume of $1.8 \mu L/cm^2$. (This translates into an 18µm thick layer.) The Project believes that such a limited volume would not allow the formation of aggressive solutions within the crevices. Finally, in the Project's view, processes occurring after any possible initiation of localized corrosion would limit the extent of the corrosion. Those processes include corrosion stifling, physical retention of brine in the corrosion products, and chemical sequestration of brine components in the corrosion products. The scientist presented some preliminary data to support the Project's claims about stifling and used the data to argue that the answer to the fifth question is "no" as well.

Drip Shield. In mid-1998, the Project decided to introduce a drip shield into its baseline design of the proposed repository system. Current plans call for the drip-shield base to be made from Alloy-22; the drip-shield shell, plates, and welds from titanium-grade 7; and the drip-shield structural supports from titanium-grade 24.

Although titanium-grade 7 generally is considered not susceptible to stress-corrosion cracking (SCC) at below-boiling temperatures in neutral or basic solutions, one set of experiments at 105ºC showed apparent SCC when this material was immersed in concentrated basic saturated water (BSW). Based on this finding, the Board felt it important to pursue the question of whether titanium-grade 7 is the appropriate material for the drip shield.

At the Board's November 8, 2005, meeting, a Project scientist gave a comprehensive presentation on the potential degradation of the drip shield as a result of corrosion (Gordon 2005). He noted that experiments indicated that the titanium might be susceptible to hydrogen induced cracking (HIC) in the presence of fluoride ions. However, the aerated repository conditions and the extended period of dry oxidation likely provide a sufficient margin of protection against HIC. Further, a repetition in air rather than in BSW of the SCC experiment that prompted the Board's question gave essentially the same results as the earlier experiment. This finding suggests that crack growth observed in the BSW tests may have been due primarily to creep rupture, not to SCC.

It should be noted that the TSPA assumes that penetrations of the drip shields due to any SCC that might occur would be limited to fine cracks through which no water would flow, especially if the cracks are filled with corrosion products and mineral assemblages (Boyle and Lachman 2005). The Project has carried out preliminary experiments to support this assumption.

2. Board Findings and Recommendations

The Alloy-22 outer barrier of the waste package will not corrode significantly unless liquid water is present on the waste package surface. The higher the temperature at which liquid water is present, the greater is the concern, because metals generally corrode faster at higher temperatures and the susceptibility of metals to corrosion generally increases at higher temperatures. Project scientists have determined that dusts from ventilation air during the preclosure period would settle on waste package surfaces and would contain sodium chloride, sodium nitrate, potassium nitrate, and other salts. Certain combinations of these salts, dissolved in water, could form saturated brines with boiling points on the order of 200ºC.

The Project maintains that potential localized corrosion of Alloy-22 at elevated temperatures can be excluded from its TSPA calculations. The Board believes that the technical basis for the exclusion is not compelling, partly because only very limited corrosion data have been collected at temperatures above 150ºC and partly because data showing cessation (stifling) of localized corrosion at lower temperatures may or may not be relevant to all conditions under which localized corrosion could occur in the proposed repository (Garrick 2005c). The Project will participate in a Board-sponsored public workshop in September 2006 to address this issue in greater depth. The Board strongly urges the Project to continue collecting data that might justify its assumption that general corrosion will not occur at temperatures as high as 200ºC.

Besides the potential for localized corrosion, aqueous conditions on waste package surfaces at elevated temperatures raise other corrosion concerns. General corrosion of Alloy-22 is a very slow process, but it is the process by which waste packages inevitably will fail if they do not fail first because of localized corrosion (or because of SCC, see below). General corrosion proceeds more rapidly at higher temperatures. Some previous performance assessment models have assumed that general corrosion of Alloy-22 *does not occur above 120ºC,* presumably based on the assumption that aqueous conditions do not exist above this temperature. Because aqueous conditions *can* exist at elevated temperatures —as Project researchers have demonstrated— future performance assessments should not exclude general corrosion at elevated temperatures when aqueous conditions are predicted to be present. The Board strongly urges the Project to continue to collect data to resolve the issue of whether general corrosion occurs at temperatures as high as 200ºC.

Alloy-22 has been shown to be very resistant to, but not immune from, SCC under many Yucca Mountain conditions at temperatures below approximately 160ºC. Although Alloy-22 can exhibit SCC under these conditions, very high stress intensities induced by pre-cracking are required, and even then cracks propagate very slowly. However, for Yucca Mountain environments above about 160ºC, only limited SCC data exist for Alloy-22. Given that the susceptibility of metals to SCC generally increases with temperature, the Project will have to obtain relevant data under higher-temperature conditions, assume that SCC will occur, or use a different approach.

The Project has gathered substantial new data on SCC of the titanium-grade 7 alloy used to construct the drip shield. Nonetheless, the Board continues to believe that SCC in titanium alloys cannot be dismissed.

If the waste packages corrode to the point where water can enter them, the SNF cladding and the fuel pellets also must degrade before waste gets mobilized and leaves the package. Alternatively, the glass with which the HLW has been mixed must degrade. Although there is good understanding about what radionuclides will be present in the SNF and the HLW at the time of emplacement and how those radionuclides will decay over time, the Project's understanding of how the radionuclides interact with the SNF and glass-degradation products is much more limited. Consequently, there is considerable uncertainty about the source term incorporated into the TSPA. To address this uncertainty or lack of detailed analysis, the Project has made simplifying assumptions that need to be reviewed carefully for their effects on the fuel degradation and radionuclide migration processes.

For example, the Project has presented experimental data on SNF alteration where neptunium-uranium co-precipitation did not occur, suggesting that neptunium transport may not be significantly delayed by this process. Further, drip-test data show neptunium concentrations that are not necessarily at that radionuclide's solubility limits. The Board notes that the Project is seeking to improve its understanding of the source term through research sponsored by its Science and Technology program. Even if such work is not incorporated directly into the TSPA, it will likely increase confidence in technical claims that will be advanced by the Project (Garrick 2005c).

D. The Postclosure Risk Associated with the Proposed Repository

Beginning in 1991, the OCRWM carried out seven performance assessments for the proposed repository at Yucca Mountain, and it is in the process of preparing an eighth assessment, the TSPA-LA. If submitted to the NRC, the TSPA-LA will be the focus of an adjudicatory hearing to determine whether the DOE will be permitted to construct a repository at Yucca Mountain.

1. The OCRWM's Technical and Scientific Investigations

At the November 9, 2005, meeting, the Project sought to address two general questions posed by the Board: To what extent does the TSPA rely on conservative or non-conservative assumptions? What effect do those assumptions have on projections of repository performance?

Two Project scientists advanced three key positions (Van Luik and Andrews 2005):

- The primary purpose of performance assessment is to demonstrate post-closure regulatory compliance.
- The DOE will provide a demonstration of post-closure regulatory compliance that does not underestimate dose.
- This demonstration demands the application of a cautious but reasonable approach in modeling long-term performance.

The two individuals cited NRC regulations, publications from international bodies, such as the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development, and the Board itself in defense of those positions. Further, they suggested that the use of conservative assumptions was unavoidable given that models have to be simplified, that needs for additional data have to be reduced, and that alternative conceptual models have to be addressed. In contrast, they maintained that in no case has the TSPA been intentionally non-conservative or optimistic.

The two scientists provided three examples of conservatism used in the TSPA. In the first example, EBS transport, they pointed to conservatisms, among other things, dealing with coupled processes in the breached waste packages, the representation of the water film on the waste form and in-package materials, and the in-package chemical conditions. In the second example, transport of radionuclides in the unsaturated zone, they noted that a cautious but reasonable approach had been adopted to propagate future climate effects and to represent site-scale matrix diffusion processes. In the third example, transport of radionuclides in the saturated zone, they observed, among other things, that permanent filtration of colloids is not considered and that potential reducing conditions were not incorporated.

They concluded their presentation by noting that the Project is able to understand the implications of using conservative representations by undertaking sensitivity analyses. This approach allows them to defend the conclusions reached in the TSPA. Although the Project continues to explore ways of making its performance assessments less conservative and more realistic, there probably are practical limits on what might be done in this area. Ultimately, the two scientists suggested, the Project is not likely to change any of its three key positions.

At the Board's February 1, 2006, meeting, a third scientist described a "scoping" performance assessment that was carried out to 1,000,000 years, which included the time of peak dose (Nutt 2006). This performance assessment contained a number of simplifications:

- Only representative FEP's that could potentially affect peak dose were evaluated.
- A constant climate state was used, which is based on an integrated long-term average. This resulted in slightly larger infiltration rates than occur during the glacial transition climate stage.
- Repository average percolation flux was set equal to average infiltration.
- Drifts were presumed to have collapsed because of seismic activity.
- Only advective radionuclide transport was considered.
- Only general corrosion processes were evaluated.
- Waste forms were presumed to degrade instantaneously once the waste packages failed because of general corrosion.
- All transport through the volcanic rocks of both the unsaturated and saturated zones was assumed to be instantaneous. Radionuclide transport in the saturated alluvium was included in the model.

The Project scientist identified three factors from the scoping study that are significant to the size and timing of the peak dose: waste package lifetime, neptunium solubility, and magnitude of water seepage. Neither igneous nor seismic events were expected to have a significant effect on peak annual dose.

The presentation did not include any quantitative performance assessment results, although they were publicly available, having been included in a document containing the DOE's comments on the EPA's proposed environmental standard (Golan 2005b). That document reports the following:

- Waste packages begin to fail at 480,000 years and continue to fail beyond 1,000,000 years.
- The drip shields begin to fail at 40,000 years and continue to fail until about 1,000,000 years. If drips shields were not deployed,

the peak dose would rise by approximately 20 percent.

- The peak dose occurs at roughly 600,000 years. Its mean value is approximately 100 mrem/year.

- If the temperature dependence on the waste package general corrosion rate was extended below 45°C to 21°C, the time of the peak dose would be pushed out beyond 1,000,000 years, but its magnitude would remain approximately the same.

At its February 1, 2006, meeting, the Board also heard a presentation on conservatism, non-conservatism, and uncertainty in radiation-dose calculations that are part of a risk-informed analysis (Ryan 2006). The presentation identified five approaches for addressing conservatisms and uncertainties:

- Extreme bounding analysis;

- Bounding analysis;

- Sensitivity studies;

- On-off calculations and comparisons; and

- Probabilistic risk analysis.

Examples of past uses of each approach were presented to demonstrate that each can play a role in dose calculations, each has strengths and weaknesses, and some may be better than others for specific applications.

2. Board Findings and Recommendations

Scientists and engineers are typically cautious in advancing claims. They usually prefer to wait until as much evidence as possible has accumulated before committing to a particular position. To borrow from the language that the EPA used in its recently proposed Yucca Mountain standard, this "natural tendency" is reenforced when those individuals know that their claims might be challenged in a formal regulatory process.

The Board appreciates the fact that the Project is in the midst of preparing a license application for its proposed repository system. Not surprisingly, the Project is motivated to advance a licensing case whose main—and possibly sole—objective is to demonstrate compliance with the applicable regulations via an intensely legalistic process. Consequently, when faced with gaps in understanding, "bounding" or conservative approaches often are adopted. Examples of this abound, including how the Project models the temperature dependence of generalized corrosion rates, sorption in the saturated zone, and the containment capability of some parts of the EBS. What is difficult to assess is the degree of total conservatism that exists when scientists add their own conservatism in the chain of integrated analyses that form the TSPA.

For that reason, the Board remains concerned that by adopting a conservative compliance-focused approach, the Project discounts the importance of letting policy-makers, the public, and the broader technical and scientific community know what the Project's experts believe are the intrinsic capabilities of the proposed repository at Yucca Mountain. Having more definitive information on the adequacy of the natural system and the levels of conservatism involved, for example, may well provide all interested and affected parties with important and relevant information.

The Board believes that the Project's "cautious but reasonable" approach to dealing with uncertainties has limits, including the fact that just how conservative the TSPA is overall is unclear. This limit is not overcome by conducting sensitivity analyses because the effects of parameter and model changes related to one component of the examined system or subsystem may be masked by assumptions about other components of the system or subsystem. Thus, the Board believes that the Project should carry out a realistic performance assessment, perhaps in parallel with its efforts to develop a compliance case. Such a realistic performance assessment would establish a "baseline" for measuring how "conservative" or "non-conservative" the Project's licensing case might be. A realistic performance assessment also is likely to increase confidence in the conclusion reached in the Project's compliance-focused TSPA.

To conduct these realistic analyses, scientists and engineers should be asked to give their best assessment of performance-critical parameters. The assessments should reflect not only the experts' opinions about the value of performance-critical parameters but also the uncertainties involved. Including the uncertainties in the assessments communicates the experts' confidence in their state of knowledge—an important piece of evidence. Responding convincingly to the request for such information may require increased understanding of the repository system. In addition, although some assumptions still may be required, they, too, will need to be well justified if this best assessment is to be carried out credibly. Thus, the Board reiterates its view that fundamental understanding is important and encourages the Project to fill in areas where significant gaps in such understanding exist (Garrick 2005c, 2006).

To address what now appears to be the critical radionuclides contributing to peak dose, the Board recommends that the Project prepare full and realistic process models that account for the transport of the two radionuclides in question, ^{237}Np and ^{242}Pu. Such an effort would involve tracing the radionuclides from when they leave the degraded fuel pellet until they are taken up by the "reasonably maximally exposed individual." These analyses should be consistent with the thermal hydraulic analyses used in the thermal-management strategy. The model calculations should extend until the time of peak dose or 1,000,000 years (Garrick 2006).

E. Design and Operation of Surface and Subsurface Components and Facilities

In recent years, the Project has intensified its efforts to design and develop concepts-of-operation for the surface and subsurface facilities that might be constructed at Yucca Mountain. Many of these are first-of-a-kind facilities.

1. The OCRWM's Technical and Scientific Investigations

Surface components and facilities. At a January 20, 2004, Board panel meeting (NWTRB 2004a), a Project engineer presented plans for constructing several surface facilities for handling SNF and HLW: a transportation cask-receipt facility, a canister-handling facility, and two dry-transfer facilities (Harrington 2004). At the Board's September 20, 2004, meeting (NWTRB 2004c), another Project engineer provided an update on the Project's work on surface facility design (Craun 2004). In a November 30, 2004, letter to the OCRWM, the Board expressed concern that the operation of the planned surface facilities could result in bare SNF assemblies being handled as many as four times, amounting to close to one million handling operations for bare fuel assemblies. The Board recommended that the Project find ways to minimize the number of times that the assemblies would be handled (Garrick 2004).

During 2005, technical problems arose in the design of the dry-transfer facility including whether its atmosphere could be effectively made inert. Largely because of these problems, the Project decided to reassess its plans for building many of the surface facilities. Out of that reassessment came the TAD concept, which, among other things, aims to reduce the amount of bare SNF handling, and thus the radiation exposure of workers (Arthur 2005). As noted above, any final decision to develop the TAD could have important implications for the Project's thermal-management strategy.

At present, little information is available on the new surface facility design. The Board is awaiting design information to assess the improvements that have been made to the original design concepts.

Subsurface components and facilities. In the period covered by this report, Project scientists and engineers made three presentations on the drip shield's design and how it might be put into operation. At the Board's February 9, 2005, meeting, two Project scientists described how the concept of a drip shield emerged from the multimaterial waste package concepts considered by the Project's License Application Design Study undertaken in the late 1990s (Boyle and Lachman 2005). Although both Alloy-22 and titanium were evaluated for use in this component of the EBS, titanium was selected to avoid potential material common-mode failures and to increase the level of defense-in-depth.

At the Board's November 8, 2005, meeting, a Project engineer detailed the drip shield's functional and operational requirements (Anderson 2005). The component had to be designed so that it would not preclude waste package retrieval. Further, it had to prevent seepage entering the drift from dripping onto the waste packages after repository closure and had to protect the waste packages from direct impacts from rockfall.

The drip shields would be installed by remote control just before repository closure, which could occur any time from 50 to 300 years after waste emplacement begins. A gantry would straddle a drip shield segment and lift it up. The gantry would then move the segment down the drift. Next, the drip shield segment would be positioned and aligned with a previously installed segment. The drip shield segment then would be lowered so that the two segments interlocked. To accomplish these tasks, the Project would have to design and build an emplacement gantry, a gantry transporter, a drip shield transporter, and a transport locomotive. Those designs are at their earliest stages of development.

A second Project engineer described analyses that examined how the drip shield would respond to mechanical degradation caused by potential seismic events (Board 2005). The analyses evaluated the effects of drift degradation, including rockfall and vibratory motion, as well as fault displacement. The analyses concluded that the drip shield would be structurally stable even after the collapse of the drifts. Further, the drip shields would be structurally stable even after being struck by the largest and most highly energetic rocks. Finally, the drip shields would remain interlocked under the full range of seismic shaking conditions.

Representing the State of Nevada, an engineer provided a different assessment of the drip shield's functionality (Kendorski 2005). Among the potential problems he noted were the following:

- The drip shield transport gantry may be hard to recover if it becomes inoperable in the drift.
- The tight clearances in the emplacement drift may be hard to navigate because the dusty environment can obscure the video images that are critical for remote control.
- Verifying that interlocking of the drift shield segments has been achieved successfully may be difficult. This may be particularly important because the interlocking tolerances are very small.

He concluded by observing that if the drip shield is integral to safety, there must be "an up-front and credible plan and design" for how the drip shield will be installed. Based on his review of the Project's documents, no such plan and design currently exist.

2. Board Findings and Recommendations

The Board looks favorably on the Project's provisional decision to implement the TAD concept. It believes that such an approach holds the potential for minimizing the handling of bare SNF assemblies, for simplifying the design of surface facilities, and for reducing occupational exposures (Garrick 2005b, 2005c). Clearly, the success of such an approach requires close cooperation and coordination among the DOE, utilities, and cask vendors. Based on its fact-finding meeting with representatives of utilities and cask vendors, the Board believes that steps are now being taken to promote that cooperation and coordination. As noted above, however, the Board remains concerned that the Project has not fully evaluated the range of consequences associated with implementation of the TAD concept, especially with respect to thermal management.

Thus, the Board recommends that the Project conduct a formal analysis that addresses, among other things, the following areas:

- What are the performance specifications of the TAD? How were they derived?
- How does the introduction of the TAD affect logistic capabilities and limits?
- What constraints on SNF blending does the TAD create?
- How does the TAD affect surface facility design and operation?
- How does the TAD affect the sequencing of waste emplacement necessary to maintain the specified line load of 1.45 kW/meter?

The Board believes that the Project needs to refine further its drip shield design and implementation approach (Garrick 2005c). Although the Project has produced some analytical results that it believes show that the drip shield interlocks will withstand seismic events, it is hard to believe that the drip shields will maintain their "as-installed" configuration even as those same events cause the waste packages to fail. Further, the Board believes that the Project needs to address issues related to in-drift operational envelopes and installation tolerances that could potentially increase the difficulty of installing the drip shields remotely. Finally, because the drip shield will not be installed until just before repository closure, which will be many years after waste emplacement has begun, the Project should evaluate now what factors will affect the final design of this EBS component and explain how, when, and by whom decisions about installing drip shields will be made, including whether to install them at all.

F. Plans for the Waste-Management System

The waste-management system consists of elements that collectively must carry out a range of functions: accepting waste at a utility or, if needed, at DOE defense-complex sites; handling, transporting, processing, and storing the waste; and, finally, emplacing the waste underground. Because the elements of the waste-management system are tightly coupled, the assessment of the behavior and performance of one element may strongly depend on or affect the behavior and performance of others.

1. The OCRWM's Technical and Scientific Investigations

Total System Model (TSM). At the Board's February 9, 2005, meeting, the manager in charge of system integration discussed the TSM, which was then being developed (Kouts 2005a). The Project intends to use the TSM to analyze and integrate the set of activities that start with the acceptance of SNF and HLW at utility and DOE sites, continue with the transportation of the waste to the proposed repository, and end with the handling and management of the material in facilities located on the surface near Yucca Mountain.

The TSM is an event-driven, real-time simulation. Objects, such as SNF assemblies or casks, can be traced from receipt to emplacement. The model can be used to simulate the actions of filling waste packages to meet thermal constraints, to evaluate alternative acceptance, transportation, or management scenarios, and to challenge existing design and operating concepts. Two sample results derived from the TSM—the cumulative receipt of commercial SNF shipping casks and the requirements for procuring large rail casks—were presented. At the Board's November 9, 2005, meeting, the same manager provided the Board with a somewhat fuller explanation of the TSM (Kouts 2005b).

Transportation Network. At the Board's February 10, 2005, meeting, the manager in charge of transportation gave two presentations (Lanthrum 2005a, 2005b). The first provided an update on the activities of his office. He laid out for the Board the major activities for which he had responsibility: cask acquisition, rolling-stock acquisition, development of transportation support facilities, transportation operations, construction of a Nevada rail line, and institutional relations. He explained how the various activities are interrelated and affect each other. He noted that many activities have had to be trimmed or deferred because the OCRWM did not receive from Congress the budget that it had requested. For instance, for FY05, the OCRWM requested $125 million for transportation but only $25 million was appropriated or approximately 40 percent of what it had received in FY04. In FY06, OCRWM's transportation budget is slightly less than $20 million.

Nonetheless, work continued on the Nevada Rail Alignment Environmental Impact Statement, conceptual design work for rail casks, and development relationships with four State Regional Groups. In July 2005, following the release of a U.S. Department of Transportation (DOT) study on the advantages and disadvantages of using dedicated trains to move SNF and HLW (DOT 2005), the OCRWM announced that it was "adopting a policy to use dedicated trains for its usual shipments of spent nuclear fuel to the Yucca Mountain repository site in Nevada, when the repository is operational…" (Golan 2005a). In December 2005, the OCRWM released its *Environmental Assessment for the Proposed Withdrawal of Public Lands Within and Surrounding the Caliente Rail Corridor, Nevada* (OCRWM 2005).

2. Board Findings and Recommendations

Because the elements of the waste-management system are tightly coupled and because the assessment of the behavior and performance of one element may strongly depend on or affect the behavior and performance of others, the Board believes that it would be a mistake to try developing the system without recognizing and accommodating these interdependencies. Thus, the Board notes that the Project has begun development of the TSM, which has significant potential as a tool for understanding the performance of the waste-management system. For example, the TSM can be used to examine system throughput, to identify possible "choke" points, and show where various design and operational elements are incompatible; it can assess the effects of delayed construction of a rail spur; and it can evaluate the conditions that contribute to efficient operation of the surface facilities. For maximizing the value of the TSM, however, the input data must be based on the most up-to-date information; critical modeling assumptions must be confirmed; there should be an ability to represent upset conditions; and all waste-management system components, including emplacement, should be incorporated into the model.

Further, the Board recommends that the Project enhance the TSM in the following ways to increase the model's utility in evaluating the waste-management system:

- Add a system optimization module.
- Allow for stochastic processing times.
- Incorporate the effects of contingent events, such as major storms, bridge collapses, and delays in the construction of key facilities and system components.

The Board further recommends that the enhanced TSM be used by designers of the surface facilities and all other waste-management system components to determine needs and capabilities and to eliminate problems or constraints in the future.

The Project also should evaluate phased approaches to developing the waste-management system. For example, it should consider handling "normal" SNF first and exceptional fuel types at a later date. It should consider early shipments that are easy to load, use a single transport mode, travel over a relatively short distance, and following of routes used previously in shipping radioactive materials. It might also consider "bundling" plants with common practices into the same waste acceptance phase.

Because of funding constraints, much of the Project's anticipated work on establishing a transportation network has been deferred. Nonetheless, the Board believes that the Project should move expeditiously to perform a comparative risk analysis of alternative rail corridors that might be used to move SNF and HLW to Yucca Mountain. Once that risk analysis has been completed, the DOE should inform all interested and affected parties what route(s) it prefers. In addition, the Project should develop a contingency plan for greater use of legal-weight and heavy-haul trucking. The Project also should supplement its current "top-down" route-selection efforts that rely on State Regional Groups with a "bottom-up" mode of interaction involving direct and meaningful input from potentially affected first responders and community leaders. Finally, the Board recommends that the Project manage its emergency response grant program using a systems approach that incorporates anticipated responses to accident conditions during transportation and verifies that adequate emergency response capability exists along each transportation route.

III. Other Board Activities

A. Site Visits

In June 2005, a delegation of Board members and staff visited the Peach Bottom Atomic Power Station, located in York County, Pennsylvania. The facility, operated by the Exelon Corporation, is the home to two boiling water reactors and one small experimental reactor that was taken out of service in 1974. The Board greatly appreciates the willingness of the Exelon Corporation to host this visit and to ensure that it was a productive one for the Board.

The purpose of the visit was to observe one day of a week-long activity during which SNF assemblies were removed from the reactor SNF pool and loaded into a dry storage-transportation cask. The Board delegation also viewed the transporter that carries the loaded cask to the storage pad. In addition, the visit gave the Board delegation an opportunity to understand better the critical interface between a utility and the OCRWM's waste-acceptance program.

In July 2005, a delegation of Board members and staff visited the DOE's Waste Isolation Pilot Plant (WIPP), located in Carlsbad, New Mexico. The WIPP is the only operating geologic repository for long-lived radioactive waste. Beginning in 1999, transuranic-contaminated (TRU) waste from the DOE's nuclear weapons complex has been disposed of in the WIPP's salt formations. Waste emplacement is expected to continue for approximately another 30 years.

The purpose of the visit was to observe the operations of a repository. The Board delegation also examined the transportation casks used to bring TRU waste to the WIPP. The delegation went underground and saw where new drifts were being constructed. In addition, it observed some of the emplaced TRU waste. The Board delegation met with DOE officials to hear what lessons they believed they had learned during the course of developing the WIPP repository. The Board delegation also met with Carlsbad's mayor and other community leaders to get their impressions of events that ultimately led to the WIPP's opening. The Board thanks the WIPP officials and scientists and the leadership of the Carlsbad community for making this a constructive and valuable site visit.

In November 2005, a delegation of Board members and staff visited the DOE's Savannah River Site, where the Defense Waste Processing Facility (DWPF) had poured nearly 2,000 of the planned 5,060 canisters of glass containing HLW. The canisters produced so far hold approximately four percent of the radioactivity of the HLW stored in the tanks at the site. Also at the Savannah River Site is the L-Reactor spent-fuel pool, where all DOE-owned SNF is being consolidated. This SNF eventually will be packaged at the L-Reactor and transported to the DWPF. There it will be combined with canisters containing HLW and sent to the proposed repository at Yucca Mountain. Facilities for managing the DOE-owned SNF once it leaves the L-Reactor spent-fuel pool have not been designed. The Board greatly appreciates the DOE's willingness to host this site visit and to provide important information to aid in the Board's technical review.

B. International Activities

The Board continues its exchanges with other national radioactive waste management programs to keep informed of developments of potential importance to the United States and to broaden the Board's perspective in its efforts to review the Project.

For example, the Board has an informal working agreement with the Swedish National Council for Nuclear Waste (KASAM). The KASAM evaluates the work undertaken by Swedish Nuclear Waste Company (SKB), the utility-owned organization responsible for implementing that country's nuclear waste program. In March 2005, a small Board delegation attended a seminar sponsored by the KASAM. The main purpose of the seminar was to review and discuss the SKB's latest three-year plan for waste management research, development, and demonstration.

On April 2005, the mayor and other representatives from the municipality of Oskarshamn, Sweden paid a visit to the Board's office. They were in Washington with a group of 33 representatives from municipalities in Sweden at which nuclear facilities are located. The Oskarshamn delegation visited separately with Board representatives and provided their perspectives on the site-characterization process in Sweden. Board members presented their perspectives on developments in the United States program.

In conjunction with its own meeting, the Board hosted the third meeting of the Advisory Bodies to Government (ABG) in Las Vegas on January 30 through February 2, 2006. This group was organized in early 2004 under the auspices of the NEA. The ABG's purpose is to provide a forum for organizations similar to the Board to meet and exchange information and to share experiences in their successes and setbacks in accomplishing their assigned missions. Countries that have established entities somewhat similar to the Board in purpose and scope are: France, Germany, Japan, Sweden, Switzerland and the United Kingdom.

Each of these countries sent at least one representative to the meeting to present updates on their review work, describe the status of their respective programs, and discuss issues of mutual interest. In addition, the delegates met and exchanged views with representatives from the Nevada and California counties surrounding the proposed repository site. Many of the ABG delegates also toured Yucca Mountain, Amargosa Valley, and Ash Meadows National Wildlife Refuge.

C. Board Letter on Criticality

On February 18, 2005, the Board responded to a letter about criticality from the State of Nevada's Agency for Nuclear Projects (Garrick 2005a). The Board stated that it had reviewed a recent DOE report (OCRWM 2004) on the probability of internal criticality. According to the report, the probability of the combined failure of waste packages and drip shields during the 10,000-year period following repository closure, a necessary precondition for criticality, would be well below the level of regulatory significance for the so-called nominal case, which assumes no significant earthquakes or volcanic events. The Board found this conclusion to be credible.

Subsequently, the Environmental Protection Agency proposed changes to its radiation safety standard applying to a Yucca Mountain repository in August 2005 (EPA 2005), and the Nuclear Regulatory Commission proposed changes to its regulation applying to a repository at Yucca Mountain in September 2005 (NRC 2005). The proposed changes are significant, particularly the proposals to change the period of applicability from 10,000 years after repository closure to the period extending from repository closure up to the time when peak dose is predicted to occur up to 1,000,000 years after repository closure. The proposed changes would not require the DOE to estimate the probability or consequence of internal criticality beyond 10,000 years after closure if the estimate of the probability of internal criticality during the 10,000-year period after repository closure is below the level of regulatory significance.

The final versions of the proposed changes have not been issued as of the date of publication of this report. The Board will continue monitoring all of the DOE's ongoing developments and activities related to in-repository criticality and the technical bases underlying the DOE's criticality calculations.

IV. The Board in Transition

In May 2005, Dr. Daryle Busch submitted to President Bush his resignation as a member of the Board, effective July 15, 2005. Dr. Busch, former President of the American Chemical Society, is Roy A. Roberts Distinguished Professor of Chemistry at the University of Kansas. In the short time that Dr. Busch served on the Board, he brought strong technical insights and sound judgment to his evaluation of the DOE's work at Yucca Mountain.

V. The Board's Plans for 2006

The Board will organize its work in 2006 into three major areas. The first is preclosure operations. This area includes an examination of the TAD concept and the technical basis for the OCRWM's decision on whether to proceed with implementation of the TAD. It also includes the design of surface facilities at the proposed Yucca Mountain site. In addition, the Board will evaluate any comparative risk assessment of alternative transportation modes and routes that the OCRWM might conduct.

The second major area is postclosure performance of the proposed repository. The Board will continues its evaluation of the Project's investigations of the elements constituting the natural and engineered barriers. The Board intends to pay particular attention to work undertaken to understand better seepage into drifts, waste degradation, including waste package corrosion and radionuclide transport out of the EBS, and flow and transport of dose-significant radionuclides into the biosphere.

The third major area is integration of the waste management system. The Board will continue its efforts to evaluate the technical basis for the Project's thermal management strategy. It will explore how the Project trades off preclosure and postclosure risks. It will also evaluate any realistic performance assessment that the OCRWM might conduct.

Abbreviations and Acronyms

ABG	Advisory Bodies to Government
BSC	Bechtel-SAIC Corporation
Board	U.S. Nuclear Waste Technical Review Board
BSW	basic saturated water
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DWPF	Defense Waste Processing Facility
EBS	engineered barrier system
EPA	U.S. Environmental Protection Agency
FEP’s	features, events, and processes
GNEP	Global Nuclear Energy Partnership
HIC	hydrogen induced cracking
HLW	high-level radioactive waste
KASAM	Swedish National Council for Nuclear Waste
kW	kilowatt
LA	license application
MTHM	metric tonnes heavy metal
NEA	Nuclear Energy Agency
NRC	U.S. Nuclear Regulatory Commission
NWPAA	Nuclear Waste Policy Amendments Act of 1987
NWTRB	U.S. Nuclear Waste Technical Review Board
OCRWM	Office of Civilian Radioactive Waste Management
Project	Yucca Mountain Project

SCC	stress-corrosion cracking
SKB	Swedish Nuclear Waste Company
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
TAD	transport-aging-disposal
TRU	transuranic-contaminated
TSM	Total System Model
TSPA	Total System Performance Assessment
USGS	U.S. Geological Survey
WIPP	Waste Isolation Pilot Plant

Glossary

The following list was compiled to help readers understand some of the terms used in this report.

advective transport The movement of radionuclides by the bulk mass of flowing fluid.

Alloy-22 A nickel-chromium-molybdenum alloy proposed for use as the material of construction for the waste package's outer wall.

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

analogue (analog) A phenomenon that can provide information on or add understanding to aspects of repository performance. Analogues are of two types: natural and anthropogenic. Natural analogues occur through natural phenomena. Anthropogenic analogues result from human activity. An "archaeological analogue" is an anthropogenic analogue resulting from the activities of ancient cultures.

backfill Natural or engineered aggregates placed in drifts to restrict human intrusion, to mitigate drift degradation and rock fall and the effects of seismic events on the engineered barrier system.

barrier A natural or engineered system that prevents or mitigates the movement of radionuclides toward the accessible environment.

brine A concentrated solution of one or more salts in water.

bomb-pulse See **chlorine-36**

bounding analysis Using extreme parameter estimates to project repository performance.

burnup A measure of reactor fuel consumption expressed as the percentage of fuel atoms that have undergone fission, or the amount of energy produced per unit weight of fuel.

cladding The outer layer of a nuclear fuel rod.

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 1950s temporarily increased concentrations of chlorine-36. The resulting "bomb-pulse" levels of chlorine-36 can sometimes serve as a tracer to determine how rapidly precipitation from the 1950s has moved through soil and rocks such as those present at Yucca Mountain.

colloid A state of subdivision of matter in which the particle size varies from that of true "molecular" solutions to that of coarse suspensions with the diameter of the particles lying between 10^{-7} and 10^{-5} centimeters.

conservative Projections of repository performance using parameters and models that systematically under-estimate the system's ability to isolated and contain waste.

corrosion A destructive attack of a material by chemical or electrochemical interaction with its environment.

coupled processes The effects of heat on geochemistry and on the movement of water in either the liquid or gaseous phases.

cross-drift A small exploratory tunnel across the waste emplacement area of the proposed repository to enable scientists to get a preview of the geologic and hydrologic conditions.

defense-in-depth The use of multiple barriers in the design of the proposed repository to make the system less vulnerable to failure if a single barrier fail to function as anticipated.

deliquesence The absorption of atmospheric water vapor by a solid salt to the point where the salt dissolves into a saturated solution.

dissolved species A chemical in aqueous solution.

dose See **radiation dose**

drift An underground opening or tunnel that is used for access/egress, to facilitate repository construction, ventilation, and transportation and emplacement of nuclear waste.

drip shield Barriers placed over and around waste packages to divert water from the packages and deflect falling rocks from impacting the waste package.

engineered barrier system (EBS) The constructed components of a disposal system designed to retard or prevent releases of radionuclides from the underground facility. Such components include waste forms, fillers, waste containers, shielding placed over and around such containers, and backfill materials.

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

fault displacement Relative movement of two sides of a fault such as that which occurs during an earthquake.

fuel rod An engineered structure that consists of a rod or tube, typically made of zircaloy, into which fuel material, usually in the form of uranium oxide pellets, is placed for use in a reactor. Many rods or tubes, that are mechanically linked, form a fuel assembly or fuel bundle.

gantry The rail-mounted transportation system used remote remotely emplacement of waste packages and drip shields.

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

groundwater Subsurface water as distinct from surface water.

high-level radioactive waste (HLW) Highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in concentrations above levels specified in regulations. Any other highly radioactive material that the Nuclear Regulatory Commission, consistent with existing law, determines requires permanent isolation by disposal in a geologic repository.

igneous **f**ormed by volcanic activity.

infiltration The flow of a fluid into a solid substance through pores or small openings; specifically, the movement of water into soil or porous rock.

invert The natural or engineered floor configuration of a tunnel or underground opening.

License Application (LA) A document submitted to the Nuclear Regulatory Commission containing general information and a safety analysis for certain nuclear facilities such as a nuclear power plant, a geologic repository, and a spent-fuel storage facility. A license application must be approved before the facility is constructed and before it can be operated.

line-load Two distinctly different emplacement strategies for waste package within and emplacement drift. A line load refers to placement such that the waste packages are virtually end-to-end or nearly touching. Point load refers to placement such that the packages separated by a least 2m.

lithophysal Volcanic rock containing hollow bubble-like cavities formed by gases as they cool.

localized corrosion Corrosion that takes place at discrete sites, for example, in waste package crevices.

matrix The solid framework of a porous system.

matrix diffusion The migration of higher concentrations of dissolved chemicals from more permeable zones to zones that are less permeable zones and that have lower concentrations of the same dissolved chemicals.

multiple lines of evidence Varied methodological approaches used in combination to infer the behavior of the repository system (or its major components) for extended time periods. Examples of individual methods include analogues, simplified calculations, and arguments based on defense-in-depth.

natural barriers Attributes of the earth that tend to isolate radionuclides from the human-accessible environment.

near field A zone that typically extends one diameter outward from the tunnel wall. In that zone, coupled thermal, hydrological, mechanical, and chemical processes are expected to occur.

Nuclear Waste Policy Act (NWPA) The federal statute enacted in 1982 that established the Office of Civilian Radioactive Waste Management and defined its mission to develop 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 the states, local governments, and Indian tribes.

Nuclear Waste Policy Amendments Act (NWPAA) The federal statute enacted in 1987 that amended the Nuclear Waste Policy Act by limiting repository site-characterization activities to Yucca Mountain, Nevada; establishing the Office of the Nuclear Waste Negotiator to seek a state or Indian tribe willing to host a repository or monitored retrievable storage facility; creating the Nuclear Waste Technical Review Board; and increasing state and local government participation in the waste management program.

oxidizing Any chemical reaction that involves the loss of electrons from an atom or ion.

peak dose The maximum radiation dose-rate projected to occur after the closure of the repository.

peer review A documented critical review performed by those who have experience at least equal to those who performed the work being reviewed but who are independent from individuals who performed the work.

percolation flux The movement of water through the repository horizon per unit area per unit time.

performance assessment A complex computer-based analysis that projects how well the entire repository system will isolate and contain waste and what the human health consequences will be if waste reaches the biosphere.

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 repository performance objectives for the period after permanent closure will be met.

postclosure The time after the closure of the geologic repository.

preclosure The time before and during the closure of the geologic repository.

process models Conceptual and mathematical models of a particular process (e.g. unsaturated-zone flow) that reflects the phenomena of interest. The models then can be abstracted (simplified) for use in performance assessments.

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

radionuclide An atomic nucleus that is radioactive.

radionuclide migration or radionuclide transport The movement of radioactive materials through rock formations, typically in water.

reducing Any chemical reaction that involves the gain of electrons by an atom or ion.

repository See **geologic repository**

risk analysis Estimates of the probability multiplied by the consequences of a specific event or condition.

saturated zone The part of the Earth's crust in which all empty spaces are filled with water.

seismic Pertaining to an earthquake or earth vibration.

sensitivity analysis A type of performance analysis in which particular parameters are varied to obtain insights into their effect on waste isolation and containment and human health.

site suitability A determination by the U.S. Department of Energy that on the basis of data and analysis that a proposed repository site is likely to meet the EPA's environmental standard. Such a determination in the case of Yucca Mountain led the Secretary of Energy to recommend to the President that an application for construction authorization be developed and submitted to the Nuclear Regulatory Commission. Congress ultimately approved this recommendation.

Site-suitability Guidelines Criteria set forth in 10CFR963, that are to be used by the U.S. Department of Energy in assessing the suitability of the site.

sorption Retardation of water-transported radionuclides as a result of their physically or chemically bonding to surfaces of geologic materials along the flow path.

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 (SNF) Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by chemical reprocessing.

SNF assembly See **fuel rod**

stress corrosion cracking (SCC) A cracking process in materials that results from simultaneous corrosion and sustained tensile stress.

thermal-management strategy A plan for maintaining the waste form, cooling system, facility, and natural and engineered barrier systems temperatures within design limits.

thermal pulse The period of approximately one thousand years immediately following repository closure, during which temperatures on the waste package surface can rise to more than 150°C, according to the Department of Energy's current repository design.

thermohydrology The study of coupled water and heat flow.

Total System Model (TSM) A tool to analyze the linkages, interactions, and synergies between the waste acceptance, transportation, and the repository. A model capable of integrating and analyzing the waste management system performance, alternative system solutions and assessing program and policy impacts.

Total System Performance Assessment (TSPA) Term used by the U.S. Department of Energy to describe the particular performance assessments conducted to determine with the proposed Yucca Mountain repository complies with the relevant regulatory requirements for waste isolation and containment and protection of human health.

transparent Easy to detect or observe. The use of clear language and easily understood concepts and/or assumptions to arrive at credible, traceable, and logical conclusions.

unsaturated zone Layers of rock in which some, but not all, of the empty spaces are filled with water.

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

waste management system All elements of the system involved in the management of radioactive wastes.

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

References

Anderson, M. J. 2005. "Drip Shield Configuration and Emplacement." Presentation to U.S. Nuclear Waste Technical Review Board. November 8, 2005. Las Vegas, Nevada.

Andrews, Robert. 2005. "Science and Modeling Update." Presentation to U.S. Nuclear Waste Technical Review Board. February 9, 2005. Las Vegas, Nevada.

Arnold, Bill W. 2006. "Mass and Activity of Key Radionuclides Potentially Released from the Saturated Zone Over Time." Presentation to U.S. Nuclear Waste Technical Review Board. February 1, 2006. Las Vegas, Nevada.

Arthur, W. John, III. 2005. "Office of Repository Development Project Update." Presentation to U.S. Nuclear Waste Technical Review Board. February 9, 2005. Las Vegas, Nevada.

Birkholzer, Jens T. 2006. "Mass of Water Seeping into Drifts Over Time." Presentation to U.S. Nuclear Waste Technical Review Board. February 1, 2006. Las Vegas, Nevada.

Board, Mark. 2005. "Mechanical Degradation of the Drip Shield." Presentation to U.S. Nuclear Waste Technical Review Board. November 8, 2005. Las Vegas, Nevada.

Boyle, William J. and Kirk Lachman. 2005. "Integration of Total System Performance Assessment (TSPA) and Repository Design." Presentation to U.S. Nuclear Waste Technical Review Board. February 9, 2005. Las Vegas, Nevada.

Bryan, Charles R. 2005. "Localized Corrosion Due to Dust Deliquesence on the Alloy 22 Waste Package Outer Barrier." Presentation to U.S. Nuclear Waste Technical Review Board. November 8, 2005. Las Vegas, Nevada.

Chu, Margaret S. Y. 2005. January 26 letter from Margaret S. Y. Chu, Director, Office of Civilian Radioactive Waste Management, to B. John Garrick, Chairman, U.S. Nuclear Waste Technical Review Board, on the Department of Energy's responses to recommendations in the Board's July 28, 2004, letter.

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

________. 2000. March 20 letter from Jared L. Cohon, Chairman, U.S. Nuclear Waste Technical Review Board, to Ivan Itkin, Director, Office of Civilian Radioactive Waste Management, on the use of performance assessment to estimate long-term repository behavior.

________. 2002. March 11 letter from Jared L. Cohon, Chairman, U.S. Nuclear Waste Technical Review Board, to Lake H. Barrett, Acting Director, Office of Civilian Radioactive Waste Management, containing Board's comments on presentations at the January Board meeting.

Corradini, Michael L. 2003a. June 30 letter from Michael L. Corradini, Chairman, U.S. Nuclear Waste Technical Review Board, to Margaret S. Y. Chu, Director, Office of Civilian Radioactive Waste Management, on initial Board reactions to presentations at the May Board meeting.

________. 2003b. October 21 letter from Michael L. Corradini, Chairman, U.S. Nuclear Waste Technical Review Board, to Margaret S. Y. Chu, Director, Office of Civilian Radioactive Waste Management, on the Board's comments on data and analyses related to corrosion presented at the May Board meeting.

Craun, Richard. 2004. "Repository Design Status." Presentation to U.S. Nuclear Waste Technical Review Board. September 20, 2004. Las Vegas, Nevada.

Department of Energy. Office of Civilian Radioactive Waste Management (OCRWM). 2004. *Screening Analysis of Criticality Features, Events, and Processes for License Application,* ANL-EBS-NU-000008 REV 01, October 2004.

________. ________. 2005. *Environmental Assessment for the Proposed Withdrawal of Public Lands Within and Surrounding the Caliente Rail Corridor, Nevada.* DOE/EA 1545. Las Vegas, Nevada.

________. ________. 2006. *Evaluation of Technical Impact on the Yucca Mountain Project Technical Basis Resulting From Issues Raised By Emails of Former Project Participants.* DOE/RW-0583. Las Vegas, Nevada.

________. Office of Public Affairs. 2005. "Statement from Secretary of Energy, Samuel Bodman." March 16 press release. Washington, D.C.

________. ________. 2006. "Technical Report Confirms Reliability of Yucca Mountain Work." February 17 press release. Washington, D.C.

Department of Transportation (DOT). 2005. *The Use of Dedicated Trains for Transportation of High-Level Radioactive Waste and Spent Nuclear Fuel: Report to the Congress, March 2005.* Washington, D.C.

Duquette, David J. 2004. July 28 letter from David J. Duquette, Chairman, Executive Committee, to Margaret S. Y. Chu, Director, Office of Civilian Radioactive Waste Management, on the Board's reactions to presentations at the May Board meeting.

Environmental Protection Agency (EPA). 2005. "Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada: Proposed Rule." *Federal Register*. Vol. 70, No. 161. August 22, 2005; pp. 49013–49065.

Garrick, B. John. 2004. November 30 letter from B. John Garrick, Chairman, U.S. Nuclear Waste Technical Review Board, to Margaret S. Y. Chu, Director, Office of Civilian Radioactive Waste Management, conveying the Board's comments on the information presented at the September Board meeting.

________. 2005a. February 18 letter from B. John Garrick, Chairman, U.S. Nuclear Waste Technical Review Board, to Robert R. Loux, Executive Director, Agency for Nuclear Projects, State of Nevada, on criticality.

________. 2005b April 19 letter from B. John Garrick, Chairman, U.S. Nuclear Waste Technical Review Board, to Theodore Garrish, Deputy Director, Office of Civilian Radioactive Waste Management, on the Board's reactions to presentations at the February Board meeting.

________. 2005c. December 19 letter from B. John Garrick, Chairman, U.S. Nuclear Waste Technical Review Board, to Paul M. Golan, Director, Office of Civilian Radioactive Waste Management, on the Board's reactions to presentations at the November Board meeting.

________. 2006. March 6 letter from B. John Garrick, Chairman, U.S. Nuclear Waste Technical Review Board, to Paul M. Golan, Director, Office of Civilian Radioactive Waste Management, on the Board's reactions to presentations at the February Board meeting.

Golan, Paul M. 2005a. July 18 letter from Paul M. Golan, Director, Office of Civilian Radioactive Waste Management, to Stakeholder, on the adoption of a policy to use dedicated trains for the shipment of spent nuclear fuel and high-level radioactive wastes to the Yucca Mountain repository.

________. 2005b. November 21 letter from Paul M. Golan, Director, Office of Civilian Radioactive Waste Management, to EPA Docket Center, Air and Radiation Docket conveying the Department of Energy comments on proposed revisions to EPA Rule 40 CFR Part 197, August 22, 2005.

Gordon, Gerald M. 2005. "Drip Shield Creep and Environmental Degradation Update." Presentation to U.S. Nuclear Waste Technical Review Board. November 8, 2005. Las Vegas, Nevada.

Hardin, Ernest. 2006. "Rate of Water Flow out of Repository Drifts Over Time." Presentation to U.S. Nuclear Waste Technical Review Board. February 1, 2006. Las Vegas, Nevada.

Harrington, Paul. 2004. "Repository Design Status." Presentation to U.S. Nuclear Waste Technical Review Board. January 20, 2004. Las Vegas, Nevada

________. 2005. "Project Operational Thermal Management Strategy." Presentation to U.S. Nuclear Waste Technical Review Board. February 9, 2005. Las Vegas, Nevada.

Ilevbare, Gabriel. 2005. "Effects of Dust Deliquescence on Localized Corrosion of the Waste Package Outer Barrier (Alloy 22)." Presentation to U.S. Nuclear Waste Technical Review Board. November 8, 2005. Las Vegas, Nevada.

Kendorski, Francis S. 2005. "Review and Critique of Drip Shield Concept and Retrieval Concept Planned for the Yucca Mountain Project, Nevada." Presentation to U.S. Nuclear Waste Technical Review Board. November 9, 2005. Las Vegas, Nevada.

Kouts, Christopher. 2005a. "Systems Integration." Presentation to U.S. Nuclear Waste Technical Review Board. February 9, 2005. Las Vegas, Nevada.

________. 2005b. "Systems Integration and Total System Model." Presentation to U.S. Nuclear Waste Technical Review Board. November 9, 2005. Las Vegas, Nevada.

Lanthrum, Gary. 2005a. "Office of National Transportation Update." Presentation to U.S. Nuclear Waste Technical Review Board. February 10, 2005. Las Vegas, Nevada.

________. 2005b. "Planning the Nevada Rail Branch Line." Presentation to U.S. Nuclear Waste Technical Review Board. February 10, 2005. Las Vegas, Nevada.

Nuclear Regulatory Commission (NRC). 2005. "Implementation of a dose standard after 10,000 years: proposed rule." *Federal Register*. Vol. 70, No. 173. September 8, 2005; pp. 53313–53320.

Nuclear Waste Technical Review Board (NWTRB). 2001. *Report to the U.S. Congress and the Secretary of Energy: January to December 2000*. Arlington, Virginia.

________. 2003. "An Evaluation of Key Elements in the U. S. Department of Energy's Proposed System for Isolating and Containing Radioactive Waste." U.S. Nuclear Waste Technical Review **Board Technical** Report. Arlington, Virginia.

________. 2004a. Panel on the Engineered System meeting; January 20, 2004; Las Vegas, Nevada (transcript of proceedings). Arlington, Virginia.

________. 2004b. Spring Board meeting; May 18–19, 2004; Washington, D.C. (transcript of proceedings). Arlington, Virginia.

________. 2004c. Fall Board meeting; September 20, 2004; Las Vegas, Nevada (transcript of proceedings). Arlington, Virginia.

________. 2005a. Winter Board meeting; February 9–10, 2005; Las Vegas and Caliente, Nevada (transcript of proceedings). Arlington, Virginia.

________. 2005b. Fall Board meeting; November 8–9, 2005; Las Vegas, Nevada (transcript of proceedings). Arlington, Virginia.

________. 2006. Winter Board meeting; February 1–2, 2006; Las Vegas, Nevada (transcript of proceedings). Arlington, Virginia.

Nutt, W. Mark. 2006. "Management and Technical Support Peak Dose Sensitivity Analysis." Presentation to U.S. Nuclear Waste Technical Review Board. February 1, 2006. Las Vegas, Nevada.

Ryan, Michael T. 2006. "Conservatism, Nonconservatism and Uncertainty in Dose Calculations – Risk Informed Dose Calculations." Presentation to U.S. Nuclear Waste Technical Review Board. February 1, 2006. Las Vegas, Nevada.

Sassini, David and Rob Howard. 2006a. "Mass and Activity of Key Radionuclides Potentially Released from Waste Forms, Waste Packages and Drifts Over Time." Presentation to U.S. Nuclear Waste Technical Review Board. February 1, 2006. Las Vegas, Nevada.

Sassini, David and Rob Howard. 2006b. "Mass and Activity of Key Radionuclides Potentially Released from Waste Forms, Waste Packages and Drifts Over Time." Presentation to U.S. Nuclear Waste Technical Review Board. February 1, 2006. Las Vegas, Nevada.

U.S. Congress. 1987. *Nuclear Waste Policy Amendments Act of 1987* (NWPAA). 100th Congress, 1st Session, 1987. Washington, D.C.: Government Printing Office.

Van Luik, Abraham and Robert Andrews. 2005. "Conservatisms in DOE's Performance Assessments: Role and Example." Presentation to U.S. Nuclear Waste Technical Review Board. November 9, 2005. Las Vegas, Nevada.

10 CFR 63 (Code of Federal Regulations). 2001. Title 10, *Energy*, Part 63, "Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain."

40 CFR 197 (Code of Federal Regulations). 1999. Title 40, *Protection of Environment*, Part 197. "Environmental Radiation Protection Standards for Yucca Mountain, Nevada." Washington, D.C.: Government Printing Office.