U.S. NUCLEAR WASTE
TECHNICAL REVIEW BOARD

Report to
The U.S. Congress
And
The Secretary of Energy

January 1, 2003, to December 31, 2003

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UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
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May 2004

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

The Honorable Ted Stevens
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable E. Spencer Abraham
Secretary
U.S. Department of Energy
Washington, DC 20585

Dear Speaker Hastert, Senator Stevens, and Secretary Abraham:

The 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 (NWPA) of 1982. In this report, the Board summarizes its major activities from January 1, 2003, through December 31, 2003.

During that period, the Board continued its evaluation of the technical and scientific validity of the U.S. Department of Energy (DOE) activities related to the disposal, packaging, and transportation of spent nuclear fuel and high-level radioactive waste. The Board held meetings and commented to the DOE on a range of technical and scientific issues, including seismicity, DOE plans for transporting the waste, the design and operation of facilities at the proposed repository site, performance- confirmation activities, and the potential for localized corrosion of waste packages during the period of high temperatures after repository closure. Correspondence and related materials from the Board to the DOE on these and other issues are included in the appendices to the report. Also included in the appendices are the Board's

strategic plan for fiscal years 2004-2009, its performance plans for 2004 and 2005, and its performance evaluation for 2003.

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

We thank you for this opportunity to present the Board's views.

Sincerely,

David J. Duquette
Executive Committee Chairman

NUCLEAR WASTE TECHNICAL REVIEW BOARD 2003

[1] Resigned effective January 12, 2004
[2] Resigned effective January 17, 2003

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Executive Summary

In 1987, the U.S. Nuclear Waste Technical Review Board (Board) was created as an independent federal agency by Congress in the Nuclear Waste Policy Amendments Act. The Board was charged with evaluating the technical and scientific validity of the U.S. Department of Energy's (DOE) efforts to develop a system for disposing of high-level radioactive waste and spent nuclear fuel. The Board is required to report its findings and recommendations to Congress and the Secretary of Energy at least twice a year. This document describes activities undertaken by the Board from January 1 through December 31, 2003.

In the year following Congress's approval of the Yucca Mountain, Nevada, site for development of a repository, the major focus of the Board's activity was its evaluation of the DOE's analysis of how corrosion-resistant its Alloy 22 waste package was likely to be. The Board devoted one full meeting and parts of two others to exploring this question. The Board wrote two letters to the DOE communicating its findings and recommendations. The Board also prepared a detailed 18-page technical analysis to support its conclusions.

In its October 21, 2003, letter to the DOE, the Board raised concerns about the performance of the waste package if it is subjected to conditions that are likely to arise if the DOE implements its current high-temperature repository design. In particular, the Board made the following observations.

- Localized corrosion processes are particularly insidious because initiation is difficult to predict and propagation rates can be very rapid. Data emerging both from the DOE's Yucca Mountain Project and from the Nuclear Regulatory Commission's Center for Nuclear Waste Regulatory Analyses (CNWRA) suggest to the Board that crevice corrosion of Alloy 22 is likely to begin during the thermal pulse (the first thousand years after repository closure).

- Project data show that initiation of crevice corrosion during the thermal pulse is likely in concentrated brines (with or without nitrates) formed through deliquescence processes at temperatures well below the peak temperatures on the waste package surface expected in the DOE's proposed repository design.

- Crevice corrosion, a form of localized corrosion, initiated during the thermal pulse is likely to propagate during the remainder of the thermal pulse and also is likely to continue even after the thermal pulse has passed.

- Work at the CNWRA and elsewhere indicates to the Board that welds and thermal treatment (aging) increase susceptibility to crevice corrosion. The DOE's modified waste package design has both welded areas (i.e., closure welds) and many features that offer opportunities for crevice formation. Redesign studies for reducing or eliminating areas of increased susceptibility to localized corrosion may be a worthwhile option.

- Most generalized corrosion data reported to date are for surface temperatures on the waste package of 95°C or lower. These data may constitute an adequate technical basis if the surface temperatures of the waste packages in the repository never exceed 95°C. Few data exist, however, for the higher temperatures of the thermal pulse.

- Because of the seriousness of these corrosion concerns, the Board strongly urges the DOE to reexamine the current repository design and proposed operation. The Board believes that the high temperatures of the current design and operation will result in perforation of the waste packages, with possible release of radionuclides. The data currently available to the Board indicate that perforation is unlikely if waste package surface temperatures are kept below 95°C.

- Finally, the Board believes that total system performance assessment should not be used to dismiss these corrosion concerns.

In its November 25, 2003, letter to the DOE, the Board stated that, based on its review of data gathered by the DOE and the CNWRA, all the conditions necessary to initiate localized corrosion of the waste packages likely will be present during the thermal pulse because of the deliquescence of salts on waste package surfaces, and thus the initiation of deliquescence-induced localized corrosion will be likely during the thermal pulse. In particular, corrosion experiments indicate that localized corrosion is likely to be initiated if temperatures on the waste package surface are above 140°C and if concentrated brines, such as would be formed by the deliquescence of calcium and magnesium chloride, are present. Limited data examined to date indicate that dust, which would be present in the proposed tunnels and which would be deposited on waste packages, contains calcium chloride and magnesium chloride salts in amounts sufficient for the development of concentrated brines through deliquescence. The letter concluded, "Thus, the Board believes that under conditions associated with the DOE's current high-temperature repository design, widespread corrosion of the waste packages is likely to be initiated during the thermal pulse. Once started, such corrosion is likely to propagate rapidly even after conditions necessary for initiation are no longer present. The result would be perforation caused by localized corrosion of the waste packages, with possible release of radionuclides."

In addition to its evaluation of the DOE's analysis of how corrosion-resistant its Alloy 22 waste package was likely to be, the Board evaluated and communicated to the DOE its findings and recommendations on several other issues. They included the DOE's efforts to increase confidence in its estimates of repository performance, the DOE's plans for developing a system to transport high-level waste and spent nuclear fuel from sites where those materials are currently stored to Yucca Mountain, the DOE's analysis of seismicity issues associated with repository design, and the DOE's projections of the consequences for waste isolation and containment of igneous activity at Yucca Mountain.

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 (DOE) to develop a geologic repository system for disposing of high-level radioactive waste (HLW) and spent nuclear fuel (SNF) produced by the nation's nuclear defense complex and commercial nuclear power plants.

Between January 1, 2003, and December 31, 2003, the period covered by this report, the Board focused most of its attention on the DOE's analysis of how the waste packages might perform if they were emplaced in the proposed repository at Yucca Mountain, Nevada. In addition, the Board evaluated several DOE activities designed to increase confidence in projections of long-term repository performance. The Board also reviewed the DOE's plans for developing a transportation system that might be used to move waste to Yucca Mountain. Finally, the Board examined the DOE's analysis of issues related to earthquakes and volcanic activity.

I. Background

On July 23, 2002, President George W. Bush signed House Joint Resolution 87 (U.S. Congress 2002), formally certifying Yucca Mountain as the presumptive site for the nation's first HLW and SNF repository and authorizing the DOE to file an application with the U.S. Nuclear Regulatory Commission (NRC) for permission to construct the facility. During 2003, the DOE accelerated its efforts to prepare a license application, stepped up its work to design the surface and subsurface repository structures, and initiated efforts to create a system to transport waste from sites where it is currently stored to the proposed repository. Although the DOE's repository program entered a new phase, the Board's role remained unaltered. It continued its ongoing technical evaluation of the DOE's activities to implement the Nuclear Waste Policy Act as amended.

II. Findings and Recommendations

A. The Board's Evaluation of the Potential for Waste Package Corrosion

In its first report released in March, 1990 (NWTRB 1990) and in almost every subsequent report, the Board has raised questions about the thermal strategy that the DOE proposes to adopt for a repository at Yucca Mountain. In the early years, the Board's questions focused on the technical uncertainties that would accompany high repository temperatures, particularly temperatures above boiling.[1] Many of those uncertainties remain. For example, how might heat above boiling temperatures affect movement of water vapor in the unsaturated-zone rock where the proposed repository would be built?

[1] As will be discussed in Section III B below, this issue has arisen in other countries as well.

Over the last two years, however, data developed by the DOE and others on the corrosion of the waste package in the environment likely to be created in the DOE's current high-temperature repository design has raised several critical issues. The Board now has concluded, based on the data currently available, that all conditions necessary for penetration of waste packages by localized corrosion during the thermal pulse—the first 1,000 years after repository closure—will be present and widespread.

At its January 28, 2003, meeting in Las Vegas, Nevada, the Board heard four presentations dealing with the potential for corrosion of the DOE's proposed waste package (NWTRB 2003a). Researchers sponsored by the State of Nevada gave the first two. They described experiments and analyses designed to assess the integrity of the Alloy 22 waste package. They concluded that a wide range of corrosive conditions would be produced on the surface of the waste package, but those conditions could not be readily quantified nor could their effect on corrosion be predicted (Staehle 2003, Shettel 2003).

Investigators sponsored by the DOE gave the next two presentations. In the first one, four possible mechanisms for initiating corrosion on the waste package were evaluated: deliquescent brines from dust-water interactions, seepage brines from fracture flow, calcium chloride brines from pore water, and acid-gas evolved from calcium chloride brines (Farmer 2003a). The researcher concluded that none of the mechanisms could reasonably be expected to lead to waste package corrosion. In the second presentation, modifications made to the waste package final closure design were explained. In the DOE's view, the changes would reduce significantly the time spent welding, eliminate the need for thermal stress mitigation, reduce performance uncertainties, and achieve cost savings (Cloud 2003).

In a March 5, 2003, letter to the DOE (Corradini 2003a), the Board stated "…corrosive solutions are *possible*; the necessary pore water, decay heat from the waste packages, and in-drift conditions (i.e., high temperatures, pressure, humidity) would be present in a repository at Yucca Mountain." But the Board held that the technical basis for concluding whether the presence of those solutions was *likely* had not been established. The Board also noted that the DOE did not respond directly to a question asked at the meeting: "Would a repository with lower peak temperatures on waste package surfaces reduce the uncertainty, likelihood, or severity of the corrosive solutions?" The Board recommended to the DOE that it address that question and provide a carefully documented technical basis for its answer.

Toward that end, the Board offered the DOE broad latitude to structure as it saw fit the core of the first day of the May 13–14, 2003, Board meeting to be held in Washington D.C. (NWTRB 2003b). In response, the DOE and its contractor personnel delivered three major presentations related to in-drift thermohydrology, in-drift thermohydrochemistry, and Alloy 22 corrosion (Bodvarsson 2003, Peters 2003, Farmer 2003b).

The first presentation put forth an analysis describing why the DOE believed that there would be no seepage into the drifts of the proposed repository during the period when rock temperatures are above boiling. It also advanced the DOE's view that, if any water seeps into the drifts during that time, its chemistry would be relatively benign. The second presentation described three temperature ranges: a high-temperature regime, when rock-surface temperatures are significantly above the boiling point of water; a transition regime, when rock-surface temperatures fall between 80° and 120°C; and a low-temperature regime, when rock-surface temperatures are significantly below the boiling point of water. It also suggested reasons that neither seepage-induced nor deliquescence-induced corrosion was likely to take place. The third presentation detailed, among other things, the electrochemical analyses of waste package corrosion that had been undertaken. It also discussed results of "dip and dunk" corrosion experiments on Alloy 22. The presentation noted that there would be "zones of susceptibility" in which the environment to which Alloy 22 might be exposed would permit corrosion theoretically to occur. But it concluded that the waste package would be protected by different mechanisms in each of the three temperature ranges.

In a June 30, 2003, letter to the DOE (Corradini 2003d), the Board commended the DOE for its three presentations on the evolution of the near-field environment and on the potential for waste package corrosion. It noted, however, "…potentially significant questions remain about the technical basis for the Project's thermal analyses. These questions include concerns about the initiation of localized corrosion and the technical basis underlying Project claims about capillary and vaporization barriers. The Board is in the process of carefully evaluating the DOE's presentations from the May [2003] Board meeting and will be preparing more detailed comments for the DOE on these subjects."

At its September 16–17, 2003, meeting in Amargosa Valley, Nevada (NWTRB 2003c), the Board heard a presentation from a DOE contractor (MacKinnon 2003). It focused on how the conceptual models depicting the evolution of the near-field environment and waste package corrosion were integrated into the DOE's total system performance assessment (TSPA) and what insights were obtained. The presentation concluded the following:

- Drift seepage would not occur when [drift] crown temperatures are above the boiling point of water.
- It is highly unlikely that dust deliquescence would initiate localized corrosion on the waste package.
- If seepage water reaches the waste packages, conditions suitable for localized corrosion may occur during the thermal pulse, but the performance of the drip shield (in the nominal scenario) will prevent seepage water from contacting the waste packages, thereby making localized corrosion extremely unlikely.

In an October 21, 2003, letter to the DOE (Corradini 2003e), the Board presented its initial views about the technical validity of the DOE's claims about the potential for corrosion of the waste package. To illustrate its concerns about localized corrosion, the Board provided as an attachment to the letter copies of seven critical overheads that were shown and discussed at the Board's January and May 2003 meetings.[2] Among the key points of the letter were the following.

- Localized corrosion processes are particularly insidious because initiation is difficult to predict and propagation rates can be very rapid. Data emerging both from the Yucca Mountain Project and from the Center for Nuclear Waste Regulatory Analyses (CNWRA) suggest to the Board that crevice corrosion of Alloy 22 is likely to initiate during the thermal pulse.
- Project data show that initiation of crevice corrosion during the thermal pulse is likely in concentrated brines (with or without nitrates) formed through deliquescence processes at temperatures well below the peak temperatures on the waste package surface expected in the DOE's proposed repository design.
- Crevice corrosion, a form of localized corrosion, initiated during the thermal pulse is likely to propagate during the remainder of the thermal pulse and also is likely to continue even after the thermal pulse has passed.
- Work at the CNWRA and elsewhere indicates to the Board that welds and thermal treatment (aging) increase susceptibility to crevice corrosion. The DOE's modified waste package design has both welded areas (i.e., closure welds) and many features that offer opportunities for crevice formation. Redesign studies for reducing or eliminating areas of increased susceptibility to localized corrosion may be a worthwhile option.
- Most generalized corrosion data reported to date are for surface temperatures on the waste package of 95ºC or lower. These data may constitute an adequate technical basis if the surface temperatures of the waste packages in the repository never exceed 95ºC. Few data exist, however, for the higher temperatures of the thermal pulse.

[2] Several of the slides came from a May 14, 2003, presentation by Dr. Gustavo Cragnolino of the NRC's Center for Nuclear Waste Regulatory to the Board.

- Because of the seriousness of these corrosion concerns, the Board strongly urges the DOE to reexamine the current repository design and proposed operation. The Board believes that the high temperatures of the current design and operation will result in perforation of the waste packages, with possible release of radionuclides. The data currently available to the Board indicate that perforation is unlikely if waste package surface temperatures are kept below 95ºC.

- Finally, the Board believes that total system performance assessment should not be used to dismiss these corrosion concerns.

On November 25, 2003, the Board sent to the DOE a detailed 18-page technical report supporting the general conclusions about corrosion that it had set out a month earlier (Corradini 2003f, NWTRB 2003d). The report also contained the Board's evaluation of the technical basis underlying the DOE's claims about the evolution of the near-field environment.

Based on its review of data gathered by the DOE and the CNWRA, the Board stated that all the conditions necessary to initiate localized corrosion of the waste packages likely will be present during the thermal pulse because of the deliquescence of salts on waste package surfaces, and thus it is likely that deliquescence-induced localized corrosion will be initiated during the thermal pulse. In particular, corrosion experiments indicate that localized corrosion is likely to be initiated if temperatures on the waste package surface are above 140°C and if concentrated brines, such as would be formed by the deliquescence of calcium and magnesium chloride, are present. Limited data examined to date indicate that dust, which would be present in the proposed tunnels and which would be deposited on waste packages, contains calcium chloride and magnesium chloride salts in amounts sufficient for the development of concentrated brines through deliquescence. "Thus, the Board believes that under conditions associated with the DOE's current high-temperature repository design, widespread corrosion of the waste packages is likely to be initiated during the thermal pulse. Once started, such corrosion is likely to propagate rapidly even after conditions necessary for initiation are no longer present. The result would be perforation caused by localized corrosion of the waste packages, with possible release of radionuclides."

In its report, the Board noted that the DOE believes that the conditions in the repository would not promote significant corrosion. The Board observed that the DOE points to data, gathered using thermogravimetric apparatus (TGA), to demonstrate that the conditions necessary to initiate localized corrosion will be present only briefly. The Board, however, evaluated these data and found them inadequate to support the DOE's claim for the following reasons.

- Brines used in the TGA experiments may not be representative of those that would form on the waste packages because of deliquescence.

- The metallic coupons used in the experiments did not contain crevices.

- The TGA experiments have been run only over narrow ranges of temperature and relative humidity.

- The experimental apparatus is an "open" system that may not approximate short-term behavior of the microenvironment associated with crevices.

- The results of other experiments conducted by the DOE seem contradictory.

The Board also observed in its November 25, 2003, report that the DOE holds that the conditions under which localized corrosion might occur are extreme and unlikely. The information provided to the Board to date, however, does not form a compelling basis for that contention. For example, the DOE maintains that the presence of nitrates and an insufficient amount of calcium chloride in the proposed repository tunnels will limit localized corrosion. The DOE's own data, however, indicate that nitrate may not be protective at temperatures higher than 140°C. Furthermore, as noted above, the Board concluded that more than enough chloride would be present in the dust from the tunnels to lead to widespread localized corrosion. "Thus, the

DOE's belief that the geochemical environment on the waste package surfaces *will not* lead to corrosion lacks a strong technical basis." The Board reiterated its view that "the problems related to localized corrosion could be avoided if the repository design and operation were modified. The data currently available indicate that perforation of the waste packages caused by localized corrosion is unlikely if their temperatures are kept below 95ºC."

B. Improving Confidence in the DOE's Projections of Repository System Performance

As required by the NRC's regulations for licensing a Yucca Mountain repository, the DOE employs a complex computer-based methodology, TSPA, to project how the proposed repository might behave thousands of years into the future. The TSPA rests on a large number of assumptions, many of which are difficult to verify empirically; considerable uncertainty is attached to many of the conceptual models underlying the TSPA; and many gaps in the data used by the TSPA still persist.

Over the years, the Board has spoken often about the need for the DOE to increase confidence in its estimates of postclosure repository performance. For example, in a recent *Report to Congress* (NWTRB 1999), the Board concluded that the TSPA could be used as the "core analytical tool" for making the safety case for a repository. However, the Board also noted the limits of performance assessment and expressed doubt that relying "solely on the TSPA to demonstrate repository safety will ever be possible." Therefore, the Board recommended that additional lines of evidence, such as natural analogues, be used to overcome these limitations. Two of the four essential elements of any DOE site recommendation articulated by the Board were directed toward improving confidence in the projections of the TSPA (NWTRB 2001).

- Meaningful quantification of the conservatisms and uncertainties in the DOE's performance assessments.

- Development of multiple lines of evidence to support the safety case of the proposed repository. The lines of evidence should be derived independently of performance assessment and thus not be subject to the limitations of performance assessment.

Several times in 2003, the DOE made presentations to the Board on matters touching on confidence in the projections of repository performance. As part it of its regular update on its scientific and technical investigations at the Board's January and May 2003 meetings (NWTRB 2003a, NWTRB 2003b), the DOE discussed its efforts to reconcile contradictory analyses developed by two national laboratories related to the presence of bomb-pulse chlorine-36 at the horizon of the proposed repository. At the Board's September 17, 2003, meeting (NWTRB 2003c), the DOE informed the Board that it had approved an independent third-party study that would attempt to resolve the issue.

In a March 5, 2003, letter to the DOE (Corradini 2003a), the Board noted that the DOE has adopted the more conservative interpretation of the chlorine-36 data in developing its conceptual and numerical models of flow and transport in the unsaturated zone. Nonetheless, the Board reiterated its view that demonstrating understanding is of importance comparable to showing compliance (see NWTRB 2002). In addition, the Board maintained that discrepancies in results between two DOE-supported groups measuring the same phenomenon affect the credibility of the program. Thus, the Board "continues to believe that the DOE should persist in its efforts to reach scientific consensus on the results of the chlorine-36 analyses and the implications of those results for fluid flow in Yucca Mountain."

A potentially important independent line of evidence is the use of natural analogues to better understand how natural and engineered processes will evolve over long time periods. At its May 13, 2003, meeting (NWTRB 2003b), two speakers touched on the DOE's ongoing work at a possible analogue site at Peña Blanca in Northern Mexico. The natural uranium deposits at Peña Blanca, particularly at the Nopal 1 site, form a unique natural analogue for many of the processes that would occur at the proposed

Yucca Mountain repository. The uranium oxide deposit is in many ways similar to spent fuel. As at Yucca Mountain, it is located in oxidizing conditions in fractured, unsaturated volcanic tuff in a region of arid climate.[3]

In a June 30, 2003, letter to the DOE (Corradini 2003d), the Board observed that, on balance, Peña Blanca is an appropriate site for testing a number of important models and assumptions that underlay the DOE's analyses of Yucca Mountain and to examine alternatives to these models. Because work at Peña Blanca would likely increase understanding of important natural processes, the Board "strongly recommends continued support for studies at this unique site."

Finally, at the Board's January 28, 2003, meeting (NWTRB 2003a), a representative of the DOE's contractor discussed efforts to analyze the contributions various barriers make to the performance of the proposed repository (Swift 2003). Although this presentation was framed in the context of complying with the NRC's Yucca Mountain licensing regulation (10 CFR 63), the Board believes that such analyses also could provide important insights into the respective roles of the different barriers. Thus, in a March 5, 2003, letter to the DOE (Corradini 2003a), the Board "urged the DOE to continue this effort."

C. Development of a Waste Management System

In the NWPAA, Congress specified that one key area that the Board should review was the DOE's activities "relating to the packaging or transportation of high-level radioactive waste or spent nuclear fuel." Until recently, the DOE had undertaken very few activities related to transportation, and, consequently, the Board's review had to be limited. After Congress approved the selection of the Yucca Mountain site, however, the DOE began to devote more attention and resources to developing national and Nevada-specific transportation systems. The Board's involvement in the area also grew.

At the Board's January 28, 2003, meeting (NWTRB 2003a), the DOE presented information about the Standard Contract (10 CFR 961) negotiated between the DOE and the owners of commercial SNF, about the need to procure a transportation fleet and casks, and the process for selecting road and rail routes to Yucca Mountain from sites where HLW and SNF are currently stored (Williams 2003a). In a March 5, 2003, letter to the DOE (Corradini 2003a), the Board made three recommendations:

- The DOE's transportation planning and development effort should adopt a "systems" approach, addressing both strategic and operational considerations.

- The Board views the early involvement of external stakeholders as critical to developing a comprehensive plan for the waste management system and to building public confidence in those plans.

- Because proactive engagement of external stakeholders is a time-consuming process, the Board encourages the DOE to initiate this activity as soon as possible.

This overview was the prelude to a day-long meeting of the Board's Panel on the Waste Management System held on February 25, 2003, in Las Vegas, Nevada (NWTRB 2003f). The DOE gave a series of presentations on waste acceptance, developing a transportation plan, surface facility design and operation, and subsurface facility design and operation. The Board also invited representatives of the nuclear power industry, States through which the waste might travel, the State of Nevada, and local Nevada governments to present their views about what the DOE is doing and what it should be doing. A major purpose of this meeting was to familiarize Board members with the baseline from which the DOE will work in the years ahead.

In an April 30, 2003, letter to the DOE (Corradini 2003b), the Board conveyed the following findings and recommendations.

[3] There also are some important differences between Nopal 1 and Yucca Mountain. Scientists from the DOE and its contractors seem well aware of those differences.

- A sustained and well-thought-out effort will be needed to develop a transportation system that will engender public confidence.

- The DOE should adopt safety as a guiding principle in planning and developing a transportation system and should develop an integrated safety plan for guiding the development process.

- The DOE's strategic plan for transportation, which is being developed, should be published for public comment as soon as practical.

- The public as represented by state and local governments would like to know as soon as possible what modes and routes will be used for transporting HLW and SNF to a Yucca Mountain repository.

- The DOE should seek approaches to improving communication with utilities that will facilitate planning for the waste acceptance process.

D. Seismic Issues

Yucca Mountain is located in an area that has experienced earthquakes and volcanic activity in the past. Consequently, seismic and igneous issues have received considerable attention as the DOE characterized the site to determine whether it is suitable for repository development. Over the years, the Board has followed closely the technical work on these issues undertaken by the DOE and its contractors and generally has evaluated that work positively.

On February 24, 2003, the Board's Panel on the Natural System and its Panel on the Engineered System held a joint meeting in Las Vegas (NWTRB 2003e) to examine how the DOE is addressing a broad range of seismic issues. DOE-contractor scientists discussed the general approach taken to both preclosure and postclosure seismic issues, the basis of using particular ground-motion parameters in pre- and postclosure seismic design and analysis, and results of the preclosure analyses.[4] Finally, other DOE-contractor scientists presented analyses of drift stability and described how the response of the proposed engineered barrier system to seismic events would be incorporated in a TSPA.

To help it evaluate the information obtained at this meeting, the Board engaged the services of four experts: Alfred J. Hendron, Jr., from the University of Illinois; Peter Kaiser from Laurentian University; Art McGarr from the U.S. Geological Survey; and Anestis S. Veletsos from Rice University. Their reports (Hendron 2003, Kaiser 2003, McGarr 2003, Veletsos 2003) are available on the Board's Web site: **www.nwtrb.gov.**

In a June 27, 2003, letter to the DOE (Corradini 2003c), the Board articulated its basic concern that in estimating very-low-probability (10^{-6} per year or less) ground motions, the DOE has derived earthquake ground motions that lack physical realism and are outside the limits of existing worldwide seismic records and experience, particularly when the Yucca Mountain source and site conditions are taken into account. The Board observed that much of this critique of the very-low-probability ground motion estimates is shared by many of the individuals from the DOE and its contractor who spoke at the meeting.

The Board concluded that the estimates of very-low-probability ground motion needed to be bounded on the basis of sound physical principles. In addition, it urged the DOE to evaluate and consider the work of Dr. James Brune, the University of Nevada, Reno seismologist, who made a presentation at the February 24, 2003, meeting, as an alternative line of evidence for limiting estimates of ground motions (Brune 2003).[5] The Board also suggested how the DOE might refine its analysis of drift degradation.

[4] Preclosure refers to the roughly 100-year period after construction begins on the repository's surface and subsurface facilities. Postclosure refers to the 10,000-year period during which the repository will have to meet performance standards set by the U.S. Environmental Protection Agency and the NRC.

[5] Brune suggests using the precariously balanced rocks found on the Yucca Mountain crest to infer how much ground motion had been experienced at the site over long time periods.

The DOE defended its use of highly conservative and perhaps even physically unrealistic ground-motion estimates by claiming that the surface and subsurface facilities still would comply with applicable NRC regulations. In its letter, the Board expressed concern that "not all the assumptions in the Project's analysis of this complex, highly coupled system have been fully assessed." Thus the "true" level of conservatism may not be well specified. More generally, the Board recommended that the DOE not adopt the approach it has for six reasons:

- High levels of conservativism can lead to a skewed understanding of repository behavior and the significance of different events.

- High levels of conservatism can introduce consideration of events for which there is little or no understanding or engineering experience.

- Compounding conservative assumptions does not always produce conservative results, e.g., the worst case for drift stability is not when the horizontal and vertical stresses are both very high.

- High levels of conservatism may lead to unreasonably high costs and may have a serious effect on the eventual development of both surface and subsurface designs.

- If conservatism stems from a lack of understanding, it tends to undermine confidence in the scientific basis of the process under consideration. Physically unrealistic results, inappropriately extrapolated from physically realistic databases and analyses, could cast unwarranted doubt on much of the truly excellent work carried out in this area.

- If "unacceptable" consequences are discovered later, it may be more difficult to justify subsequent reductions of elevated ground-motion estimates previously assumed to be acceptable.

E. Igneous Issues

In 2002, the DOE chartered an independent group of technical experts to examine the issue of how igneous consequences are modeled and incorporated in the TSPA. The group's *Final Report* was released in February 2003 (ICPRP 2003). At the Board's May 14, 2003, meeting, a member of the group presented its findings and recommendations (NWTRB 2003b). To help it evaluate the issue of igneous consequences, the Board engaged the services of three scientists: Derek Elsworth from the Pennsylvania State University, William Melson from the Smithsonian Institution, and Meghan Morrissey from the Colorado School of Mines. Their reports (Elsworth 2003, Melson 2003, Morrissey 2003) are available on the Board's Web site: **www.nwtrb.gov.**

In a June 30, 2003, letter to the DOE (Corradini 2003d), the Board complimented both the DOE for initiating and supporting this peer review and the reviewers for producing a high-quality report containing much original work. The Board suggested that the DOE pay particular attention to three areas that the group explored.

- The first area is the use of upgraded modeling techniques that take into account conditions such as compressible inviscid flow that may be present at repository depth. The Board concurs with the review group that the likelihood of the generation of strong shock waves, which have been hypothesized by some investigators, is negligible.

- The second area is the need to study aeromagnetic anomalies in the vicinity of Yucca Mountain that could signify buried volcanoes. Such studies may involve additional aeromagnetic surveys (at appropriate altitudes); drilling; and dating, which could help determine the existence, age, and volume of the possible volcanoes.

- The third area is the need to address subjects that were not within the range of the Panel's expertise: i.e., waste package-magma interaction and waste entrainment in both the volcanic eruption scenario and the groundwater release scenario. The Panel confined itself to evaluating magma-drift interaction in the volcanic eruption scenario. These subjects are of great importance in any consequence analysis. The DOE should address them using the advice of outside reviewers. The DOE also

should consider experimental studies for analyzing and verifying key phenomena and parameters (e.g., chemical and mechanical effects of magma on waste packages).

III. Other Board Activities

A. Site Visits

1. Materials Testing Facilities

Board members having materials science and engineering expertise visited three major laboratories performing materials investigations relevant to the Yucca Mountain Project. The facilities were at the Lawrence Livermore National Laboratory (LLNL), the CNWRA, and The Catholic University of America (CU). Respectively, these laboratories are located in Livermore, California; on the campus of the Southwest Research Institute in San Antonio, Texas; and in northeast Washington, D.C.

LLNL is the source of virtually all the data used by the DOE to support its corrosion models for Alloy 22. Much modeling of the near-field in-drift environment also takes place at LLNL. At LLNL, Board members visited individual laboratories where data were being or had been obtained for corrosion models. They held discussions with corrosion laboratory personnel and environmental modeling personnel. The laboratory where experiments were conducted on microbially influenced corrosion particularly was impressive. Board members also toured a nearby facility where laser peening was being further developed for commercial activities. The Board members feel that LLNL's work on stress-corrosion cracking could be strengthened. They also believe that the information provided on the details of the environmental modeling and crevice-corrosion modeling was somewhat sparse. They also were disappointed in the apparent decision not to attempt to replicate CU data that recently had been made public.

The CNWRA is the principal technical arm assisting the NRC staff in the HLW and SNF areas. The materials part of the CNWRA program has produced, and continues to produce, a prodigious amount of corrosion data and associated reports. The preponderance of the CNWRA corrosion work is short term and electrochemical in nature and performed at temperatures of 95ºC or below. Some of their recent crevice-corrosion studies are done at higher temperatures but in solution chemistries different from those used by LLNL for similar studies. Modeling of the evolution of environments on waste package surfaces is performed for the NRC at the CNWRA. Apparently part of the CNWRA's environmental work is done with a modeling system (OLI) that is different from LLNL's (EQ3/6). Because modeling of high-temperature deliquescence and behavior of very concentrated brines is novel, the convergence or divergence of the results of these two modeling systems will be very important for establishing confidence.

CU is performing corrosion experiments under contract with the State of Nevada. The Board's visit was a brief one immediately after its May 2003 meeting in Washington. The evaporation of concentrated pore water to near dryness (approximately 140°C) was observed, as was the subsequent visible attack of Alloy 22 coupons by the environment thus created.

2. Peña Blanca

In May 2003, Board members visited the Peña Blanca natural analogue site, near Chihuahua, Mexico. The site is the location of an approximately 8 million-year-old hydrothermal deposit of uranium ore (as uraninite, UO_2) in older rocks. It has the following characteristics in common with Yucca Mountain: Basin-and-Range extensional tectonic setting, fractured silicic volcanic rocks, unsaturated hydrogeology, oxidizing geochemical environment, arid climate, and underlain by a carbonate aquifer. One significant difference is the presence of iron oxides coating the fractures at Peña Blanca, although iron oxides could occur at Yucca Mountain from introduced ferrous engineering materials. Another difference is that the environment at Peña Blanca was initially acidic.

The Board long has recognized the potential value of the Peña Blanca natural analogue site

and has encouraged DOE to pursue investigations there. After some initial delays, a drill rig arrived at the site to begin investigations. The new core samples and boreholes can yield a wealth of mineralogical, chemical, and isotopic information relevant to source term and radionuclide transport issues for Yucca Mountain. Mineralogical studies can address the stability of secondary uranyl phases and their chemical compositions. The stability of those minerals will ultimately control releases of much of the radionuclide inventory from Yucca Mountain. Chemical studies can inform and test reactive transport simulations. Isotope studies can be used to infer the mobility of the radionuclides and the geochemical "openness" of the system.

As noted above, the Board remains enthusiastic about the potential value of the ongoing work at Peña Blanca. It provides qualitative and quantitative insight into the character of radionuclide migration, and it provides the potential for testing process models and performance assessment tools.

B. International Fact-Finding Trips

In 2003, the Board continued to keep abreast of international scientific and technical work pertinent to the Board's mission.

For example, Board members attended the International Meeting on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement held in Reims, France. Issues discussed at the conference included approaches to analyzing technical problems, integration of scientific and technical work, the time frame for evaluating repository performance, and specific topics, such as understanding pore-water chemistry, age dating of groundwater, thermo-hydromechanical behavior, analogue work, and hydrogeological flow-and-transport modeling.

Two observations from the conference are worth noting.

- Research has been done in Spain and Switzerland aimed at understanding the thermo-hyromechanical phenomena taking place in the near field and within the engineered barrier system (bentonite, granite and/or clay). Research results indicate that it is considerably easier to predict real conditions in a potential repository using models and experiments at lower temperatures. Similar conclusions were reached by the Belgians in their research on repository design at Praclay Gallery at Mol, Belgium.

- Belgium and Sweden have produced small-scale demonstration projects of their proposed repository systems. In both countries, this exercise resulted in design changes that are still in progress, even though the initial efforts in each country were considered fairly mature at the time the projects commenced.

In October 2003, a delegation from the Board traveled to Belgium, France, Switzerland, and Britain. The purpose of the trip was threefold: (1) visit sites under study as the potential location for a repository; (2) tour long-term storage facilities and transportation systems; and (3) discuss the role of the various barriers in the disposal concepts of the countries visited, with special emphasis on waste package fabrication and performance.

A brief summary of the Board's observations obtained on this visit includes the following:

- In developing a transportation system for the proposed Yucca Mountain site, the DOE may be able to benefit by using or adapting some of the equipment, practices, and facilities developed by other countries that have already established transport systems.

- Of the countries visited by the Board that have looked at repository design issues, none proposes keeping temperatures at or above boiling for as long as the DOE proposes. In changing its reference design from a high to a low temperature, the Belgian program noted that, if temperatures are kept below boiling, it will be simpler, easier, and less complicated to understand natural processes and the behavior of materials and to make predictions.

- The experience of the Belgians illustrates that repository designs and operations can and will evolve. Such evolution is to be expected. Because pressure to build a repository is not

strong in this country, the changes do not appear to be viewed as a failure of or a roadblock to the program. Rather, the changes seem to be part of an incremental learning process of developing a design that is both safe and implementable.

IV. The Board in Transition

During 2003, two Board members tendered their resignations. On January 6, 2003, Debra Knopman informed President George W. Bush that she intended to resign from the Board effective January 17, 2003. President William J. Clinton appointed Dr. Knopman to the Board on January 17, 1997. On December 30, 2003, Michael Corradini informed President Bush that he intended to resign from the Board effective January 12, 2004. President Bush appointed Dr. Corradini as Chairman of the Board on June 26, 2002. Both Dr. Knopman and Dr. Corradini brought considerable expertise and extensive experience to the Board's task of evaluating the technical and scientific validity of DOE waste-disposal activities. During the time they served as Board members, each individual made important and valuable contributions to the Board's technical and scientific review.

V. Evaluation of the Board's Performance During 2003

The Board believes that measuring its effectiveness by directly correlating Board recommendations with improvements in the technical and scientific validity of the DOE's activities would be ideal. However, the Board cannot compel the DOE to comply with its recommendations. Consequently, a judgment about whether a specific recommendation had a positive outcome for the DOE program may be (1) subjective or (2) an imprecise indicator of Board performance because implementation of Board recommendations is outside the Board's direct control. Therefore, to measure its performance in a given year, the Board has developed performance measures. For each annual performance goal, the Board considers the following.

- Did the Board undertake the reviews, evaluations, and other activities needed to achieve the goal?

- Were the results of the Board's reviews, evaluations, and other activities communicated in a timely, understandable, and appropriate way to Congress and the Secretary of Energy?

If both measures have been met in relation to a specific goal, the Board's performance in meeting that goal is judged effective. If only one measure has been met, the performance of the Board in achieving that goal is judged minimally effective. Failing to meet both performance measures without sufficient and compelling explanation results in a judgment that the Board has been ineffective in achieving that performance goal. If the goals have been deferred, that action is noted in the evaluation.

The Board uses its evaluation of its performance from the current year, together with its assessment of current or potential key issues of concern related to the DOE program, to develop its annual performance objectives and performance-based budget request for subsequent years. The results of the Board's performance evaluation are included in its annual summary reports.

On the basis of an evaluation of its performance in meeting its goals for the year and consistent with the performance measures described above, the Board's performance for FY 2003 was found to be effective overall. However, the Secretary's activities related to the waste management program were again limited in 2003. In addition, the DOE has not undertaken some long-term design activities. Therefore, several of the Board's FY 2003 goals related to design were deferred, pending DOE activities related to the goals. A detailed evaluation of the Board's performance for FY 2003 is in Appendix H of this report.

Abbreviations and Acronyms

Board	Nuclear Waste Technical Review Board
CNWRA	Center for Nuclear Waste Regulatory Analyses
CU	Catholic University
DOE	Department of Energy
HLW	high-level radioactive waste
LLNL	Lawrence Livermore National Laboratory
NRC	U.S. Nuclear Regulatory Commission
NWPAA	*Nuclear Waste Policy Amendments Act of 1987*
NWTRB	Nuclear Waste Technical Review Board
OCRWM	Office of Civilian Radioactive Waste Management
SNF	spent nuclear fuel
TSPA	total system performance assessment

Glossary

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

aeromagnetic anomaly A localized departure from the earth's expected magnetic field as determined by an aeromagnetic survey.

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

analogue 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.

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

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

calcium chloride A highly deliquescent salt with the chemical formula $CaCl_2$.

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

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

coupon A small, thin, flat metal sample used in corrosion testing.

crevice corrosion Localized corrosion of a metal surface at or near an area that is shielded from full exposure to the bulk environment because of proximity between the metal and the surface of another material.

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

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

drip shield Barriers placed over and around waste packages to divert water from the packages.

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

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 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.

high-temperature repository design An approach that allows the temperature of the waste package surface to exceed the boiling point of water for a significant period of time.

hydrogeology The science dealing with subsurface water and with related geologic aspects of surface water.

hydrothermal Of or pertaining to hot water, to the action of hot water, or to the products of the action, such as a mineral deposit precipitated from a hot aqueous solution, with or without demonstrable association with an igneous process.

igneous Formed by volcanic activity.

inviscid flow Flow in which fluid friction is negligible.

license application 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.

localized corrosion Corrosion that takes place at discrete sites. Crevice corrosion is a form of localized corrosion.

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

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.

nitrate The anion NO_3^-, often used as a way to designate a salt containing nitrate.

Nuclear Waste Policy Act 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 The federal statute enacted in 1987 that amended the Nuclear Waste Policy Act to limit repository site-characterization activities to Yucca Mountain, Nevada; establish the Office of the Nuclear Waste Negotiator to seek a state or Indian tribe willing to host a repository or monitored retrievable storage facility; create the Nuclear Waste Technical Review Board; and increase state and local government participation in the waste management program.

peer review Critical review of a scientific report performed by experts in the subject covered in the report.

performance assessment A complex computer-based analysis that predicts the behavior of an entire repository system under a given set of conditions.

pore water Subsurface water in the voids of a rock.

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

preclosure The period of 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.

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

salt The compound formed by the anion of an acid and the cation of a base.

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

seepage The movement of liquid water, including dissolved chemicals, into repository drifts.

seismic Pertaining to an earthquake or earth vibration.

spent nuclear fuel Uranium-containing rods that have been withdrawn from a nuclear reactor following irradiation. Some of the uranium atoms have undergone nuclear reactions producing fission products and transuranic elements that remain in the rods.

Standard Contract An agreement between the U.S. Government and the owners in the United States of commercial high-level radioactive waste and spent nuclear fuel. It provides the framework under which the government will be paid by the owners to dispose of their high-level radioactive and spent nuclear fuel.

stress-corrosion cracking A cracking process in materials that results from simultaneous corrosion and a sustained tensile stress.

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.

thermal stress Forces that arise in the walls and pillars between repository drifts due to the heat from radioactive decay.

thermohydrochemistry The study of components in aqueous and solid phases as influenced by heat.

thermohydrology The study of coupled water and heat flow.

total system performance assessment (TSPA) Analyses undertaken by the Department of Energy for assessing the ability of the potential repository at Yucca Mountain to provide long-term isolation and containment of radioactive wastes.

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

waste entrainment The incorporation of buried nuclear waste into rising igneous fluids.

waste isolation Separation of the waste from the environment.

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

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