UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
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January 24, 2002

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

The Honorable Robert C. Byrd
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable Spencer Abraham
Secretary
United States Department of Energy
Washington, DC 20585

Dear Speaker Hastert, Senator Byrd, and Secretary Abraham:

Congress created the U.S. Nuclear Waste Technical Review Board (Board) in the 1987 amendments to the Nuclear Waste Policy Act and charged it with performing an ongoing independent evaluation of the technical and scientific validity of activities undertaken by the Secretary of Energy related to disposing of spent nuclear fuel and high-level radioactive waste. The Board's primary focus since its establishment has been the Department of Energy's (DOE) characterization of a potential repository site at Yucca Mountain in Nevada.

In a December 11, 2001, letter to Secretary of Energy Spencer Abraham, the Board indicated that it would comment within a few weeks to the Secretary and Congress on the DOE's technical and scientific work related to a decision on a Yucca Mountain site recommendation. Consistent with that commitment and in accordance with its congressional mandate, the Board submits this letter and attachments summarizing the results of the Board's evaluation of the DOE's work.

The Board's evaluation is based on (1) the results of the Board's ongoing review of the DOE's Yucca Mountain technical and scientific investigations since the Board's inception; (2) an evaluation of the DOE's work on the natural and engineered components of the proposed repository system, using a list of technical questions identified by the Board; (3) a comprehensive Board review of draft and final documents supplied by the DOE through mid-November 2001; and (4) field observations by Board members at Yucca Mountain and related sites. The Board's evaluation represents the collective judgment of its members. Attachments to this letter present a more detailed discussion of the Board's conclusions, the process used by the Board to arrive at its conclusions, and background information on the Board.

In evaluating the DOE's technical and scientific work related to individual natural and engineered components of the proposed repository system, the Board finds varying degrees of strength and weakness. Such variability is not surprising, given that the Yucca Mountain project is in many respects a first-of-a-kind, complex undertaking. When the DOE's technical and scientific work is taken as a whole, the Board's view is that the technical basis for the DOE's repository performance estimates is weak to moderate at this time. The Board makes no judgment on the question of whether the Yucca Mountain site should be recommended or approved for repository development. Those judgments, which involve a number of public policy considerations as well as an assessment of how much technical certainty is necessary at various decision points, go beyond the Board's congressionally established mandate.

The DOE uses a complex integrated performance assessment model to project repository system performance. Performance assessment is a useful tool because it assesses how well the repository system as a whole, not just the site or the engineered components, might perform. However, gaps in data and basic understanding cause important uncertainties in the concepts and assumptions on which the DOE's performance estimates are now based. Because of these uncertainties, the Board has limited confidence in current performance estimates generated by the DOE's performance assessment model. This is not an assessment of the Board's level of confidence in the Yucca Mountain site. At this point, no individual technical or scientific factor has been identified that would automatically eliminate Yucca Mountain from consideration as the site of a permanent repository. As discussed below, the Board believes that confidence in the DOE's projections of repository performance can be increased.

An international consensus is emerging that a fundamental understanding of the potential behavior of a proposed repository system is of importance comparable to the importance of showing compliance with regulations. The Board agrees that such basic understanding is very important. Therefore, if policy-makers decide to approve the Yucca Mountain site, the Board strongly recommends that, in addition to demonstrating regulatory compliance, the DOE continue a vigorous, well-integrated scientific investigation to increase its fundamental understanding of the potential behavior of the repository system. Increased understanding could show that components of the repository system perform better than or not as well as the DOE's performance assessment model now projects. In either case, making performance projections more realistic and characterizing the full range of uncertainty could increase confidence in the DOE's performance estimates.

The DOE's estimates of repository performance currently rely heavily on engineered components of the repository system, making corrosion of the waste package very important. High temperatures in the DOE's base-case repository design increase uncertainties and decrease confidence in the performance of waste package materials. Confidence in waste package and repository performance potentially could increase if the DOE adopts a low-temperature repository design. However, a full and objective comparison of high- and low-temperature repository designs should be completed before the DOE selects a final repository design concept.

Over the last several years, the Board has made several other recommendations that could increase confidence in the DOE's projections of repository performance. For example, the Board recommended that the DOE identify, quantify, and communicate clearly the extent of the uncertainty associated with its performance estimates. The Board also recommended that the DOE use other lines of evidence and argument to supplement the results of its performance assessment. Moreover, the DOE could strengthen its arguments concerning how multiple barriers in its proposed repository system provide "defense-in-depth" (or redundancy). Although the DOE has made progress in each of these areas, more work is needed. Other actions that might be considered if policy-makers approve the Yucca Mountain site include systematically integrating new data and analyses produced by ongoing scientific and engineering investigations; monitoring repository performance before, during, and after waste emplacement; developing a strategy for modifying or stopping repository development if potentially significant unforeseen circumstances are encountered; and continuing external review of the DOE's technical and scientific activities.

Eliminating all uncertainty associated with estimates of repository performance would never be possible at any repository site. Policy-makers will decide how much scientific uncertainty is acceptable at the time various decisions are made on site recommendation or repository development. The Board hopes that the information in this letter and its attachments will be useful to policy-makers as they make these critical decisions.

Sincerely,

Signed by all the
Board Members

Attachment 1: Details of the Board's Evaluation
Attachment 2: Information on the Board

ATTACHMENT 1

DETAILS OF THE BOARD'S EVALUATION OF THE DEPARTMENT OF ENERGY'S TECHNICAL AND SCIENTIFIC WORK

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I. INTRODUCTION

For the last two decades, the Department of Energy (DOE) has been characterizing a site at Yucca Mountain, which is in Nevada, approximately 100 miles northwest of Las Vegas, to determine whether it is suitable for developing a geologic repository to dispose of high-level radioactive waste and spent nuclear fuel from commercial nuclear reactors and the nation's atomic energy defense activities. Since inception in 1989, the U.S. Nuclear Waste Technical Review Board (Board) has evaluated the DOE's site investigations continuously. (See Attachment 2 for information about the Board and its activities.)

On January 10, 2002, Secretary of Energy Spencer Abraham notified the State of Nevada that he intends to recommend to the President that a repository be developed at the Yucca Mountain site. With that recommendation, the Secretary will initiate a process, established in the Nuclear Waste Policy Act of 1982 as amended in 1987, that could culminate several years from now in the DOE receiving a license from the U.S. Nuclear Regulatory Commission to construct a repository at Yucca Mountain.

In subsequent parts of this attachment, the Board provides more-detailed information to support the judgments made in the letter report. Section II describes the process the Board used to evaluate the DOE's technical and scientific work. Section III presents the Board's assessment of the strengths and weaknesses of the DOE's investigations and analyses of the natural and engineered components of the repository system as well as the DOE's assessment of the disruptive-events scenarios (earthquakes and igneous activity). Section IV examines how the DOE has implemented its performance assessment methodology. Section V considers how the DOE has addressed the Board's four priority areas that are essential elements of any site recommendation. Section VI looks at the natural barriers of the proposed repository system at Yucca Mountain.

II. THE PROCESS THE BOARD USED TO EVALUATE THE DEPARTMENT OF ENERGY'S TECHNICAL AND SCIENTIFIC WORK

The Board adopted a three-stage approach for reviewing and evaluating the DOE'S Yucca Mountain site-characterization work and the DOE's analysis of how a potential repository system for disposing of high-level radioactive waste and spent nuclear fuel might perform if developed at that site.

First, the Board closely examined the DOE's documented investigations and analyses of the following natural and engineered components of the repository system and the disruptive-events scenarios:

1. Unsaturated-zone flow and seepage into waste emplacement drifts
2. In-drift thermal hydrologic conditions
3. In-drift physical and chemical environment
4. Waste package degradation
5. Water diversion by the engineered barrier system
6. Waste form degradation
7. Radionuclide transport through the engineered barrier system
8. Unsaturated-zone transport of radionuclides
9. Saturated-zone flow and transport
10. Radionuclide uptake in the biosphere
11. Disruptive-events scenarios (earthquakes and igneous activity)

To focus its review of the natural and engineered components and the disruptive-events scenarios, the Board asked the following questions about each of the 11 areas listed above.

1. *Do the models used to generate input to the total system performance assessment (TSPA) and the representations of processes and linkages or relationships among processes within TSPA have a sound basis?*

2. *Have uncertainties and conservatisms in the analyses been identified, quantified, and described accurately and meaningfully?*

3. *Have sufficient data and observations been gathered using appropriate methodologies?*

4. *Have assumptions and expert judgments, including bounding estimates, been documented and justified?*

5. *Have model predictions been verified or tested?*

6. *Have available data that could challenge prevailing interpretations been collected and evaluated?*

7. *Have alternative conceptual models and model abstractions been evaluated, and have the bases for accepting preferred models been documented?*

8. *Are the bases for extrapolating data over long times or distances scientifically valid?*

9. *Can the repository and waste package designs be implemented so that the engineered and natural barriers perform as expected?*

10. *To the extent practical, have other lines of evidence, derived independently of performance assessments, been used to evaluate confidence in model estimates?*

A summary of the Board's views about the major strengths and weaknesses of the DOE's analysis of each natural and engineered component and the disruptive-events scenarios are presented in Section III of this attachment.

Second, the Board considered the degree to which the DOE addressed the four priority areas that are, in the Board's view, essential elements of any site recommendation. The Board established these priorities and communicated them to the DOE at a Board meeting held in Amargosa Valley, Nevada, on January 30, 2001. The priorities also have been reiterated and referred to in subsequent letters and reports. The four priorities are the following:

- Meaningful quantification of conservatisms and uncertainties in the DOE's performance assessments
- Progress in understanding the underlying fundamental processes involved in predicting the rate of waste package corrosion
- An evaluation and comparison of the base-case repository design and a low-temperature design
- 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.

At the same time, the Board noted that, in addition to these overarching priorities, it had made suggestions about other investigations and studies that can support, complement, and supplement these four areas. Those investigations and studies include research on the unsaturated and saturated zones as well as work on making the performance assessments more transparent and informative.

For each priority area, the Board considered how complete the DOE's efforts have been. A summary of the Board's views on how well the DOE has addressed the four priorities is in Section V of this attachment.

The third stage of the Board's deliberations involved an extended discussion of how to integrate the Board's evaluation of the various elements of the work conducted by the DOE. Individual Board members and the Board collectively arrived at an overall assessment of the DOE's technical and scientific work using a three-point scale: "weak," "moderate," and "strong."

III. FRAMEWORK FOR THE BOARD'S REVIEW OF THE DEPARTMENT OF ENERGY'S WORK RELATED TO THE NATURAL AND ENGINEERED COMPONENTS OF THE REPOSITORY SYSTEM

Taking into consideration the questions listed in Section II, the Board undertook a review of the DOE investigations and analyses of the components of the repository system. The most important questions emerging from the review are about the soundness of the models used in TSPA and the sufficiency of the database. Other important questions include the description of uncertainties and conservatism, the justification of assumptions, verification and testing of models, and the ability to implement the called-for engineering designs so that they perform as expected.

A brief description of the Board's judgment on the strengths and weaknesses of the DOE's technical work with respect to the natural and engineered components of the repository system follows. The description is intended to be illustrative but not exhaustive.

1. Unsaturated-Zone Flow and Seepage into Waste-Emplacement Drifts

Strengths include knowledge of the spatial distribution and average permeability and matrix porosity of major lithologic units, an understanding of the spatially and temporally averaged recharge rates over the last 10,000 years, and estimates of climate variability.

Weaknesses include poor understanding of the hydraulic properties of faults and other significant rock-mass discontinuities, seepage rates, and the magnitude and effects of rock-mass anisotropy. Transient hydrogeologic phenomena, including episodic recharge and resulting transient radionuclide transport, have not been analyzed adequately. In addition, there are inconsistencies between models, between model linkages, and between models and field data.

2. In-Drift Thermal-Hydrologic Conditions

Strengths include providing estimated in-drift thermal-hydrologic conditions for a range of repository temperatures.

Weaknesses include the lack of a convincing body of validating field evidence for models, inconsistencies among the in-drift thermal predictions made by different computer models, a lack of thermal-hydrologic-mechanical data (especially thermal conductivity), and incomplete accounting for the heterogeneity of the natural system.

3. In-Drift Physical and Chemical Environment

Strengths include knowledge of bulk chemical environments for low-temperature conditions and understanding rockfall under ambient conditions.

Weaknesses include lack of good understanding of local chemical environments and moisture conditions on the waste packages and of rockfall for high-temperature conditions.

4. Waste Package Degradation

Strengths include development of a short-term corrosion database and substantial experience in manufacturing materials similar to Alloy 22.

Weaknesses include lack of data on corrosion at high temperature under repository-relevant environmental conditions, no experience with metals protected by passivity for periods longer than 100 years, and limited knowledge of the fundamental mechanisms underlying long-term corrosion and passive-film behavior.

5. Water Diversion by the Engineered Barrier System

Strengths include a sound theoretical basis for the movement of liquid water through the engineered barrier system.

Weaknesses include incomplete understanding of the effects of specific temperature and humidity conditions on the performance of the drip shield, the waste package, and the invert ballast.

6. Waste Form Degradation

Strengths include understanding of radionuclide inventories, in-package chemistry, radionuclide solubilities, and use of natural analogues.

Weaknesses include incomplete understanding of cladding performance, colloid formation and dissolution, interactions of radionuclides with corrosion products, and the formation of secondary mineral phases.

7. Radionuclide Transport Through the Engineered Barrier System

Strengths include understanding of sorption of radionuclides in the invert, in-package diffusion, and diffusion through the invert.

Weaknesses include incomplete understanding of microbial and colloid-facilitated radionuclide transport in the engineered barrier system, movement from the waste package to the invert, and implementation issues associated with fabricating an invert with the desired properties.

8. Unsaturated-Zone Transport of Radionuclides

Strengths include an understanding of rock porosity on a mountain scale.

Weaknesses include an incomplete understanding of the porosity of lithophysal rock units, radionuclide- and lithology-dependent sorption coefficients, heterogeneity of the Calico Hills formation, and colloid-facilitated radionuclide transport. Moreover, the DOE's modeling of rock-matrix diffusion and radionuclide transport in the drift shadow is not well supported by field observations at this time. Nor has the DOE convincingly shown that the approach to discretization in the numerical models will not significantly influence results.

9. Saturated-Zone Flow and Transport

Strengths include understanding of the spatial distribution and large-scale isotropic hydraulic conductivity of most rock units, except the alluvium down the hydraulic gradient from Yucca Mountain, for which spatial distribution is less well known, and understanding of independent geochemical data constraining flow paths and radionuclide travel times in the saturated zone.

Weaknesses include incomplete understanding of fault hydraulic properties, site-scale boundary conditions, colloid-facilitated transport, oxidation-reduction conditions in the saturated zone, and diffusion in the rock matrix. The potential existence of a large hydraulic gradient associated with the water table configuration in the northern part of the proposed repository block has not been adequately investigated.

10. Radionuclide Uptake in the Biosphere

Strengths include a generic food-chain database associated with postulated human lifestyles and reliance on widely used and accepted codes.

Weaknesses include poorly known site-specific food chains and soil properties.

11. Disruptive-Events Scenario (Earthquakes and Igneous Activity)

Strengths include a well-developed database and understanding of earthquakes and their effects and a thorough analysis of volcanic hazard (probability of an event) at Yucca Mountain.

Weaknesses include incomplete understanding of the consequences of intrusive igneous activity.

IV. GENERAL COMMENTS ON THE DEPARTMENT OF ENERGY'S TOTAL SYSTEM PERFORMANCE ASSESSMENT

Total system performance assessment (TSPA) is the principal method for evaluating the ability of the proposed Yucca Mountain repository system and its engineered and natural components to isolate and contain harmful radioactive waste. It is a complicated, integrated mathematical model combining many linked models and submodels, most of which are directly based on physical and chemical laws and available geologic and engineering data. Given that credible alternative models exist and that relevant data sets are incomplete, TSPA also must rely on many assumptions.

Modeling the behavior of this complicated system for periods extending out to 10,000 years and beyond is, in many ways, unprecedented. There are on the order of 50 models and submodels and 1,000 parameters directly linked to TSPA, and some uncertainties are very large. Parameter uncertainties typically are caused by limited data sets and insufficient knowledge of inherent variability. Model, or conceptual, uncertainty is caused by insufficient knowledge of the processes involved. Addressing the latter type of uncertainty is both especially difficult and especially important.

There is no fully satisfactory way of validating the results of TSPA, given the time periods needed to isolate radioactive waste safely. In addition, the linkage between many of the components and parameters is so complex that often the only way to judge the effect on calculated results of changing a parameter or a submodel is through computational sensitivity tests. Although there is no problem in generating performance estimates (how well the repository system isolates and contains radioactive waste), significant efforts are needed to develop confidence in the estimates and in the overall design and safety of the repository. Confidence in TSPA and its results can be increased by recognizing and accounting for the uncertainties present and increasing the basic understanding of the repository system and its components. As noted in the December 2001 joint international peer review of the Yucca Mountain TSPA, there is an emerging international consensus that for increasing confidence, understanding should be viewed as being of comparable importance to that of showing numerical compliance with regulatory criteria.

When the DOE's technical and scientific work is taken as a whole, the Board's view is that the technical basis for the DOE's repository performance estimates is weak to moderate at this time. Consequently, although at this point no individual technical or scientific factors have been identified that would automatically disqualify the Yucca Mountain site, the Board has limited confidence in current performance estimates generated by TSPA. As discussed in Section III of this attachment, the Board's assessment is mainly due to its evaluation of the basis for the models used in TSPA and of the sufficiency of the database.

This is not to say that the DOE has not made an effort to collect the needed data and develop confidence in the needed models. The DOE has, in general, carried out an impressive, wide-ranging program aimed at understanding Yucca Mountain and the proposed repository. However, the difficulty associated with achieving that understanding has been underestimated. In all likelihood, important uncertainties always will remain. As the Board has stated in the past, TSPA by itself may never be able to show repository safety with confidence. Other means of doing so, such as expanded use of natural and engineering analogues and demonstration of multiple barriers and defense-in-depth, are discussed below in Section V.D of this attachment.

V. THE DEPARTMENT OF ENERGY'S RESPONSE TO THE BOARD'S PRIORITY AREAS FOR SITE RECOMMENDATION

A. MEANINGFUL QUANTIFICATION OF UNCERTAINTY AND CONSERVATISMS

In January 2001, the Board specified "meaningful quantification of conservatisms and uncertainties in the DOE's performance assessments" as one of its four priority areas and as an essential element of any DOE site recommendation.

Much has been learned about the Yucca Mountain site since comprehensive site characterization began about a decade ago. However, for many reasons, including the complexity of the site, the first-of-a-kind nature of the project in many respects, and the very long periods of time under consideration, uncertainties remain about components of the engineered and natural barriers that would be part of a Yucca Mountain repository system. One approach to mitigating some of the effects of uncertainty is to use conservative (or bounding) models and assumptions. Conservative models and assumptions are those whose use, in theory, would overestimate the risk to the public and provide a margin of safety. Conservative models and assumptions, however, provide unrealistic estimates of risk, and if used inconsistently and along with realistic and optimistic models and assumptions, they leave unclear the true level of conservatism and risk in calculated performance estimates.

Resolving all uncertainty is neither necessary nor possible. However, uncertainties about the performance of the components of the repository system that are relied on to isolate waste are very important, and information on the extent of uncertainty and assumed conservatism associated with the performance of those components may be important to policy makers, the technical community, and the public. For this reason, the Board has encouraged the DOE to quantify levels of uncertainty and conservatism associated with its performance assessments so that decision-makers will have a basis for weighing the extent of uncertainty and conservatism against other factors when making decisions on the Yucca Mountain site.

For the last year or so, the DOE has been engaged in an intensive and comprehensive effort to quantify the uncertainty and the conservatisms in the DOE's performance estimates. Although the DOE's efforts in this area are incomplete, the Board believes that real and important progress has been made. A primary product of this effort is *Supplemental Science and Performance Analyses* (*SSPA*), issued in July 2001. The Board found that *SSPA* is a considerable improvement over *Total System Performance Assessment for the Site Recommendation*, issued in December 2000. Improvement is defined here as reflecting a more accurate representation of reality, the state of knowledge, and uncertainties. The improvement was most substantial in the portrayal of the engineered components of the repository system and less so for the natural barrier system. Problematic areas still remain, some exhibiting substantial instability and changing substantially with each iteration of TSPA.

Another important example of this progress is a recently issued (November 2001) contractor report, *Uncertainty Analysis and Strategy*. Sound suggestions are proposed for future work on treating and communicating uncertainty. They include concentrating on realistic models and their full range of uncertainty rather than on extreme (bounding) models; quantifying uncertainties and providing the technical basis for all uncertainty assessments; addressing the difficult issue of conceptual uncertainty; using consistent definitions of “bounds” and “conservatism,” if they have to be invoked; and defining ways to communicate uncertainty effectively to decision-makers. The DOE needs to implement these suggestions, continuing the essential work of identifying, quantifying, and communicating uncertainty.

B. PROGRESS IN UNDERSTANDING FUNDAMENTAL WASTE PACKAGE CORROSION PROCESSES

In January 2001, the Board specified "progress in understanding the underlying fundamental processes involved in predicting the rate of waste package corrosion" as one of its four priority areas and as an essential element of any DOE site recommendation.

The DOE's estimates of repository performance currently rely heavily on engineered components of the repository system, making corrosion of the waste package very important. The primary corrosion barrier in the proposed package for containing spent nuclear fuel and high-level radioactive waste at Yucca Mountain is a 2-centimeter-thick shell of Alloy 22. Alloy 22 is a metal mixture containing nickel, chromium, molybdenum, and tungsten. Normally, Alloy 22 rapidly develops an ultrathin but very protective film—known as the "passive layer"—that dramatically retards corrosion of the metal. The film is essential to the corrosion resistance of the metal.

The DOE's models estimate that corrosion will not penetrate Alloy 22 waste packages for at least 10,000 years, and perhaps for longer than a million years. However, experience with Alloy 22 and comparable alloys spans only several decades, and experience with alloys that rely on passive films for corrosion resistance spans only about a century. Although a few natural or man-made materials have been identified that *might* provide insights into the long-term passivity of metals, as yet none has been confirmed as a suitable analogue. Thus, this type of corrosion resistance over many thousands of years can be extrapolated only by using theories and assumptions.

However, the theoretical basis for making such long-term extrapolations of corrosion resistance for Alloy 22 is still very limited. In addition, data on aqueous corrosion for Alloy 22 above about 120^{o} C under conditions relevant to Yucca Mountain are essentially nonexistent, creating a serious data gap. Consequently, there is great uncertainty about the performance of Alloy 22 under high-temperature conditions. Because of this uncertainty, it is difficult to be confident that waste packages would last for at least 10,000 years for repository designs that have high temperatures. Uncertainty about waste package performance lessens, however, with lower repository temperatures, because more data are available and corrosion severity generally decreases as temperatures decrease.

On the basis of the information developed by the project (and others), Board members believe that claims of minimum waste package durability of a few thousand years to a few tens of thousands of years are not out of the question under relatively mild and less uncertain in-drift conditions. These beliefs are based on the suppositions that supporting research will be continued to fill in data gaps and to rule out unexpected modes of failure and that no major "surprises" are found.

Identifying and exploring the relevant theories and assumptions and, just as important, identifying and exploring what could go wrong, particularly at times beyond the current experience base, have been considered issues of paramount importance by the Board for many years.

Over the last 16 months, the DOE has made significant progress in understanding fundamental corrosion processes. For example, the DOE retained outside consultants to develop thermodynamic models of the stability of Alloy 22 passive films and to develop models of how defects in Alloy 22 passive films could form, grow, or coalesce and affect corrosion behavior. The DOE also established a panel of experts from outside the project to review the project's corrosion and metal-selection processes. Some of the issues for the panel were the long-term performance of passive layers and how localized modes of corrosion could develop on metals such as Alloy 22.

The Board has two priorities for future corrosion work that might be conducted if the Yucca Mountain site is approved. First, to improve the DOE's ability to make reasonable long-term extrapolations, the Board believes that work on fundamental corrosion processes affecting the long-term performance of Alloy 22 should continue well beyond any positive decision on site recommendation. Second, to supplement estimates of corrosion rates developed from short-term observations and present theory, the DOE should continue its study of candidate analogues (e.g., some metallic components of the rock josephinite and metallic meteorites) and their environments and should try to identify other potential archeological analogues, natural analogues, or artifacts that might have been protected for very long periods by passive layers.

Besides improving understanding of fundamental waste package corrosion processes, many investigations of other aspects of waste package degradation are continuing. They include work to obtain short-term corrosion data at repository-relevant conditions and to fill in data gaps. They also include investigations of stress-corrosion cracking, work to determine and mitigate residual stresses at or near waste package welds, selecting specific manufacturing methods for the waste package and demonstrating them at full size, demonstrating methods for inspecting the quality of waste package manufacturing, and work to minimize manufacturing defects and premature failures. Continued efforts in these areas will be necessary if the site is approved.

C. EVALUATION AND COMPARISON OF THE BASE-CASE REPOSITORY DESIGN WITH A LOW-TEMPERATURE DESIGN

In January 2001, the Board specified "an evaluation and a comparison of the base-case repository design with a low-temperature design" as one of its four priority areas and as an essential element of any DOE site recommendation.

Understanding how the design of the repository affects tunnel environments is essential for evaluating long-term repository performance. In its August 2000 letter responding to questions from Congressman Joe Barton, the Board stated that the technical basis for the DOE's projections of repository performance had critical weaknesses, in part because of large uncertainties associated with the DOE's base-case (high-temperature) repository design. This was followed, in January 2001, by the Board's specification of an evaluation and a comparison of the base-case repository design with a low-temperature design as a priority. Although the DOE has performed some studies of hypothetical design concepts, a full evaluation and comparison of the base-case (high-temperature) and low-temperature designs as specified has not been done and is still needed.

The Board believes that a low-temperature repository design—where waste package surface temperatures would never exceed about 85º C—could offer significant advantages over a high-temperature design. Potential advantages of a low-temperature design include, as described below, (1) improving waste package performance by decreasing corrosion severity over the first 10,000 years after repository closure; (2) eliminating important uncertainties associated with moisture conditions on waste-package surfaces and waste-package corrosion during the 1,000 to 2,000 years immediately following repository closure, when waste package surface temperatures in the DOE's base-case design would be above boiling and could peak at 165º C (pure water boils at ~96º C at the elevation of Yucca Mountain); and (3) reducing important uncertainties associated with hydrologic, mechanical, and chemical processes—so called "coupled" processes that act in combination with each other.

1. Lower Corrosion Severity

Experience as well as fundamental principles of chemical kinetics indicates that corrosion severity generally decreases with decreasing temperature if other environmental conditions are constant. Because waste package surface temperatures in a low-temperature repository could be kept below 85º C, corrosion severity should be lower than in a higher-temperature case where liquid water could still be in contact with the metal.

2. Corrosion Uncertainties at High Temperatures

Alloy 22, the metal composing the outer shell of the waste package, should not corrode significantly unless aqueous conditions (i.e., liquid water) are present on the waste package surface. Recent DOE research and analyses have shown that, primarily because of deliquescence of certain very hygroscopic salts, liquid water could be present on waste package surfaces up to the peak temperature of 165º C. Although the DOE has extensive corrosion data on repository-relevant aqueous conditions at temperatures at or below 90º C, very few aqueous corrosion data exist for temperatures between 90º and 120º C at repository-relevant conditions, and essentially *no* such data exist for temperatures above 120º C.

Besides lacking high-temperature corrosion data, the DOE lacks data on how the aqueous chemical environments on waste package surfaces could evolve for above-boiling conditions, particularly for conditions between 120º C and 165º C. A special concern is the potential evolution of aqueous environments having chloride anion concentrations much in excess of "beneficial anion" (e.g., carbonate, nitrate, sulfate) concentrations, because indications are that corrosion rates could be unacceptably high under such conditions.

The Board considers these uncertainties a critical technical weakness that must be addressed if the DOE goes forward with a high-temperature design.

3. Coupled Processes and Associated Uncertainties

In its base-case (high-temperature) repository design, the DOE believes that water will vaporize (boil) and be driven away from emplacement tunnels, condense, and drain harmlessly through the pillars between the tunnels. However, observations of field heater tests (i.e., the drift-scale test and the large-block test) seem to indicate that vaporized water could, under certain circumstances, condense above the tunnels and "reflux," or drain, directly into the tunnels through existing fractures.

Furthermore, uneven heating of tunnels may create localized zones of condensation. As a result, cooler waste packages could be exposed to larger amounts of water. Drip shields (if used) could trap and condense water vapor, possibly exposing some waste packages to more water. Finally, fluctuating temperature and barometric pressure changes at the site may cause significant variations in temperature and relative humidity in the emplacement tunnels, which in turn could lead to localized zones of condensation that could migrate along the network of repository tunnels.

Tunnel walls will be compressed because of thermal expansion as tunnels heat up after waste emplacement. As tunnel temperatures decrease after a few hundred years, the rock matrix will contract, fractures will open wider, and rockfall from tunnel ceilings and seepage into tunnels could increase. Therefore, the Board believes that such spatially variable thermal-mechanical processes and their relationship to seepage into repository tunnels must be addressed further, particularly for high-temperature conditions.

Because the DOE has not determined the factors controlling refluxing or its likelihood, the Board considers this and other thermal-hydrologic unknowns related to tunnel seepage and heat-induced migration of water in and around repository tunnels in Yucca Mountain significant weaknesses.

Over the last 2 years, the DOE has produced several conceptual studies clearly demonstrating that low-temperature repository designs are feasible. The Board believes that the technical basis for operating at low-temperatures may be stronger than the technical basis for operating at high temperatures because of less uncertainty and more corrosion data available over a range of low-temperature conditions. The Board believes that the DOE will be in a stronger position to select a design concept for Yucca Mountain after preparing a low-temperature design and completing a full and objective evaluation and comparison of high- and low-temperature repository designs that identify and quantify the advantages and disadvantages of both. Strengthening the technical bases for repository design selection will require an improved understanding of the relationships among repository design and operation, the tunnel conditions thus created, and long-term waste package corrosion.

D. DEVELOPMENT OF MULTIPLE LINES OF EVIDENCE THAT ARE INDEPENDENT OF PERFORMANCE ASSESSMENT

In January 2001, the Board specified "development of multiple lines of evidence to support the safety case of the proposed repository" as one of its four priority areas and as an essential element of any DOE site recommendation.

The DOE uses a comprehensive integrated performance assessment model, Total System Performance Assessment (TSPA), to project repository performance. Using models in demonstrations of compliance for thousands of years is, in large part, unprecedented but unavoidable, given the unique circumstances of siting a repository for high-level nuclear waste. However, as discussed in Section IV, uncertainty associated with performance estimates obtained from TSPA may be large and difficult to address. For that reason, the Board has recommended over the years that the DOE supplement the results of TSPA with other lines of evidence derived independently of TSPA. This recommendation is consistent with an emerging international consensus that other lines of reasoning can increase confidence in the conclusions reached by performance assessment.

One potentially important line of evidence involves using natural and engineered analogues to obtain insights into the long-term or large-scale behavior of key repository processes and components that cannot be obtained from field and laboratory investigations. The DOE has increased its use of analogues over the last 3 years. In its latest reports, the DOE has relied on analogues for developing parameter values and ranges of parameter values that are incorporated directly in the process models that make up TSPA, for increasing confidence that appropriate values were chosen by some other means, and for increasing confidence in the soundness of a model. The DOE has not made significant use of analogues to develop insights into the performance of key components and subsystems. On the basis of what has been accomplished to date, the Board believes that the DOE's efforts in this area are incomplete but are heading in the right direction.

Although not strictly a "line of evidence," demonstrations of defense-in-depth also can increase confidence in projections of repository performance. According to the DOE, "defense-in-depth" means that the safety of a repository does not depend on the performance of any single barrier. *Repository Safety Strategy, Revision 4,* published in 2000 by TRW, then the DOE's main contractor on the Yucca Mountain Project, contained a series of "one-off" analyses that examined the effect on repository performance of reducing the effectiveness or having failure of selected barriers. In all cases, except for the waste package, the failure of a single barrier did not lead to doses higher than permitted under the relevant regulations. In addition, work undertaken as part of *Supplemental Science and Performance Analyses*, published in 2001 by the DOE, suggests that previously underemphasized barriers could provide an important degree of defense-in-depth. The most notable example of this is the role potentially played by limited radionuclide solubility.

The DOE, however, never has carried out the systematic “one-on” analyses recommended by the Board over the last 2 years. Those analyses involve the incremental addition of one barrier at a time to the repository system to understand better the factors that influence repository performance. Adding a barrier needs to be defined in a consistent manner, using the latest version of TSPA. The Board believes that such an evaluation could improve the DOE’s understanding of the effectiveness of individual barriers considerably and thus its demonstration of defense-in-depth.

VI. NATURAL BARRIERS

In January 2001, the Board specified four priority areas as essential elements of any DOE site recommendation. In addition to these overarching priorities, the Board made a number of suggestions about other investigations and studies that can support, complement, and supplement the four areas. Those investigations and studies include research on the unsaturated and saturated zones as well as work to make the performance assessments more transparent and informative.

As proposed, the potential repository for spent nuclear fuel and high-level radioactive waste at Yucca Mountain is a system composed of natural and engineered barriers. This section addresses the natural hydrogeologic barriers, in particular the unsaturated zone and the saturated zone. Evaluating the technical basis of the DOE's predictions requires consideration of the many uncertainties inherent in the complex hydrogeologic system, consideration of multiple lines of evidence from field observations and laboratory analyses, consideration of the theoretical basis underlying the predictions, consideration of the predictions themselves, and consideration of evidence from similar analogue sites.

The Board's confidence in the DOE's analysis of the ability of the natural hydrogeologic systems of Yucca Mountain to isolate radioactive waste from the accessible environment is reduced by existing uncertainties in several areas. Those uncertainties arise partly because the predictions of fluid flow and radionuclide transport in unsaturated and saturated fractured rocks is at the leading edge of the science of hydrogeology. However, those uncertainties are mitigated in part by observations of the processes of fluid flow and solute transport that have been occurring over geologic time at and around Yucca Mountain. For arriving at more realistic and technically defensible predictions of fluid flow and radionuclide transport for the range of radionuclides that DOE contemplates emplacing at Yucca Mountain, it is very important that DOE continue investigating these uncertainties. The confidence that the Board has in the DOE's analyses could be substantially enhanced with a concerted research effort over the next few years.

One indirect indicator of the extent to which the unsaturated and saturated zones at Yucca Mountain could isolate radioactive waste is "travel time." Travel time is the time required for solutes in groundwater to be transported from one point to another. As used here, those solutes are either radionuclides released from a potential Yucca Mountain repository or naturally occurring isotopes, such as radiocarbon. The hydrogeologic flow system is composed of both the unsaturated zone above the water table and the saturated zone below the water table. In the saturated zone near Yucca Mountain, water flow is down the hydraulic gradient, generally southward.

Continued investigation into uncertainties, whether resulting in shorter or longer predicted travel times, can lead to more realistic and technically defensible predictions. Uncertainties that may likely result in longer travel times include increased sorptivity and reduced solubility of radionuclides in contact with different rocks and in water with different oxidation states, possible retardation of radionuclide transport as a result of secondary mineralization, and increased matrix diffusion. The oxidation state of water in the saturated zone, and possibly in some areas of the unsaturated zone influenced by microbial activity, may either shorten or substantially lengthen travel times. Shorter travel times may result from the possible presence of isolated zones of relatively rapid flow and transport in the volcanic rocks in the saturated zone; from increased hydraulic conductivity or reduced porosity of faults in the unsaturated and saturated zones; and from potential rapid colloid-facilitated transport of plutonium and other radionuclides of similar characteristics in the saturated zone and, to a lesser extent, in the unsaturated zone.

Using multiple lines of evidence and incorporating information from relevant analogues can enhance the basis for evaluating the DOE's predictions. Geochemical data from Yucca Mountain and the surrounding region are of particular value, because the data often reflect processes that have operated over geologic time. For example, corrected radiocarbon ages of groundwater in the saturated zone approximately 20 kilometers south of Yucca Mountain range from about 6,000 to about 10,000 years, with the age within the range depending on assumptions made about the sources of carbon. Radiocarbon groundwater ages are generally interpreted by hydrogeologists to represent the average time that the groundwater has been in the flow field. However, the radiocarbon age is an average and, as such, does not reflect the likely range of travel times of contaminants spread out in a plume because of natural processes and natural variability of the hydrogeologic environment, as discussed in the following paragraph.

In *Technical Update Impact Letter Report* (Appendix G, November 2001), the DOE calculated travel times from the potential repository horizon to a hypothetical boundary in the saturated zone 18 km south of Yucca Mountain. The travel times are for an "expected" or "realistic" case of transport of conservative radionuclides and include realistic values for matrix diffusion. As used here, "conservative" means the radionuclides neither accelerated nor retarded by hydrogeochemical interactions. For an instantaneous release of a given mass of conservative radionuclides from the potential repository horizon at Yucca Mountain, the calculations indicate the following range: 10 percent of that mass would arrive at that boundary in about 2,000 years, and 90 percent of that mass would be transported that distance by about 30,000 years. The Board believes that these DOE travel-time estimates are technically credible.

Lines of evidence must be applied appropriately. Corrected radiocarbon ages pertain to conservative radionuclides; travel times for nonconservative radionuclides cannot be evaluated solely on the basis of corrected radiocarbon ages. For example, there is evidence from the Nevada Test Site that elevated concentrations of plutonium in groundwater downgradient of the locations of underground nuclear bomb tests are the result of rapid transport facilitated by extremely small particles known as "colloids." This is an example of nonconservative transport.

The DOE has not published updated calculations of radiological doses based on the recent travel time estimates in *Technical Update Impact Letter Report* (November 2001). Dose calculations require consideration of both conservative and nonconservative radionuclides in the potential repository inventory and of their particular health effects.

ATTACHMENT 2

INFORMATION ON
THE U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

INFORMATION ON THE U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

The U.S. Nuclear Waste Technical Review Board was established as an independent agency of the federal government on December 22, 1987, in the Nuclear Waste Policy Amendments Act (NWPAA). The Board is charged with evaluating the technical and scientific validity of activities undertaken by the Secretary of Energy, including the following:

- site characterization activities
- activities related to packaging and transporting high-level radioactive waste and spent nuclear fuel.

The Board was given broad latitude to review activities undertaken by the Secretary of Energy in implementing the Nuclear Waste Policy Act. However, the Board was not given authority to require the Department of Energy (DOE) to implement the Board's recommendations.

According to the legislative history, Congress intended that the Board provide ongoing advice to the DOE so that the Board's recommendations on technical and scientific issues could be considered by the DOE before decisions are made. The Board has performed this role since its inception in 1989, making recommendations intended to improve the program. In addition, as provided by law, the Board reports its findings and recommendations at least two times each year to Congress and the Secretary of Energy.

The NWPAA authorized a Board of 11 members who serve on a part-time basis, are eminent in a field of science or engineering, and are selected solely on the basis of distinguished service. The law stipulates that the Board shall represent a broad range of scientific and engineering disciplines, including environmental sciences, that are relevant to nuclear waste management. Board members are appointed by the President from a list of candidates recommended by the National Academy of Sciences. The first members were appointed to the Board on January 18, 1989. The names and affiliations of the current 11 Board members are listed below.

- Jared L. Cohon, Ph.D., became Board chairman on January 17, 1997. He is president of Carnegie Mellon University in Pittsburgh, Pennsylvania. His areas of expertise include environmental and water resource systems analysis.
- John W. Arendt, P.E., is senior consultant and founder of John W. Arendt Associates, Inc. His areas of expertise are nuclear materials facilities, quality assurance and control, and inspection.
- Daniel B. Bullen, Ph.D., is associate professor of mechanical engineering, Department of Mechanical Engineering, at Iowa State University. His areas of expertise include performance assessment modeling and materials science.

- Norman L. Christensen, Jr., Ph.D., is professor of ecology and former dean of the Nicholas School of the Environment at Duke University in North Carolina. His areas of expertise include biology, ecology, and ecosystem management.

- Paul P. Craig, Ph.D., is professor emeritus of engineering at the University of California, Davis, and is a member of the university's Graduate Group in Ecology. His areas of expertise include energy policy issues associated with global environmental change.

- Debra S. Knopman, Ph.D., is associate director, RAND Science and Technology, in Arlington, Virginia. Her areas of expertise include hydrology, environmental and natural resources policy, systems analysis, and public administration.

- Priscilla P. Nelson, Ph.D., is director, Division of Civil and Mechanical Systems, Directorate for Engineering, at the National Science Foundation. Her areas of expertise include rock engineering and underground construction.

- Richard R. Parizek, Ph.D., is professor of geology and geoenvironmental engineering at The Pennsylvania State University and president of Richard R. Parizek and Associates, consulting hydrogeologists and environmental geologists. His areas of expertise include hydrogeology and environmental geology.

- Donald D. Runnells, Ph.D., is professor emeritus in the Department of Geological Sciences at the University of Colorado. He also is a technical consultant to Shepherd Miller, Inc., environmental and engineering consultants. His areas of expertise include geochemistry, hydrochemistry, and mineral deposits.

- Alberto A. Sagüés, Ph.D., is Distinguished University Professor in the Department of Civil and Environmental Engineering at the University of South Florida. His areas of expertise include corrosion and materials engineering, physical metallurgy, and scientific instrumentation.

- Jeffrey J. Wong, Ph.D., is deputy director for Science, Pollution Prevention and Technology; Department of Toxic Substances Control, California Environmental Protection Agency. His areas of expertise include risk assessment, toxicology, and hazardous materials management.

The full Board and its five subpanels sponsor meetings and technical exchanges with program participants and interested parties, including representatives of the DOE and its contractors, the U.S. Nuclear Regulatory Commission, the U.S. Environmental Protection Agency, the U.S. Geological Survey, the U.S. Department of Transportation, the State of Nevada, affected units of local governments, Native American tribes, nuclear utilities, environmental groups, state utility regulators, and members of the public. In addition, field trips provide essential insights into the geologic, hydrologic, and geochemical processes that could affect Yucca Mountain. Since 1989, the full Board or groups of Board members have made several dozen visits to the Yucca Mountain site and surrounding regions. Board members and staff also have gained valuable insights from visiting other countries to learn about their nuclear waste disposal programs. Finally, individual Board members or small groups of members have toured laboratory facilities of the National Laboratories and DOE contractors.

Board and panel meetings are open to the public and are announced in the *Federal Register* 4 to 6 weeks before each meeting. Press releases also are issued on all public meetings. To facilitate access for program participants and the public, the Board holds most of its meetings in Nevada. Public comment sessions are included on all meeting agendas. The Board's reports, meeting transcripts, correspondence, congressional testimony, and all published documents are available on the Board's Web site at www.nwtrb.gov.