The Board's Views on "Thermal Loading"
From March 1990 through November 2002

Background: The Board was created by the Nuclear Waste Policy Amendments Act of 1987 (PL 100-203), which became law on December 22, 1987. The first eight Board members were appointed by President Reagan on January 18, 1989. Including the current ten Board members (as of February 2003), a total of 29 individuals have served as Board members.

The law requires the Board to write at least two reports yearly to the Secretary of Energy and Congress providing the Board's findings, conclusions, and recommendations. In addition, the Board Chairman and/or Board members testify before Congressional committees one or more times a year, and, since 1998, the Board has made it a practice to issue a feedback letter to the Director of OCRWM after each of the Board's public meetings. (The Board conducts three or four public meetings of the full Board each year as well as public meetings of its panels as needed.) The Board's reports, testimony, letters to OCRWM, and other correspondence of general interest are publicly available on the Board's website, www.nwtrb.gov.

Summary of Board Views on Thermal Loading: As indicated in the table of contents on the following page, the Board has been concerned about the effects of repository temperatures ("thermal loading") since its inception through its latest (November 2002) letter to the Director of OCRWM. In its first report (March 1990), the Board identified thermal loading as an important issue. The Board also linked technical uncertainties about geologic disposal with the level of thermal loading. In 1991, the Board stated that, "Different geometric layouts and thermal-loading alternatives for the repository should be explored." In October 1991, the Board conducted a three-day public meeting on the topic of thermal loading, and subsequently published, in June 1992, a report focusing on thermal-loading issues.

Initially, the Board's concerns with repository temperatures focused on "coupled" processes, i.e., the interaction of temperature with hydrologic, geochemical, and mechanical features and processes. The effects of temperatures on the waste package were a lesser concern because in the early 1990s the waste package had a comparatively minor role and was designed to last only a brief period (300-1,000 years). Later, as the importance of the waste package for repository performance increased and the package design became more robust, the Board's concern about the interaction between repository tunnel temperatures and the waste package became at least as significant as the Board's concerns about thermohydrologic, thermochemical, and thermomechanical processes.

Attachment A contains *verbatim* excerpts about thermal loading issues taken from Board writings over the years. Clear from the excerpts is that the same thermal issues identified by the Board in its early years remain present and significant, and that these issues have been compounded by serious concerns about the effects of high temperatures on waste package performance. Since the excerpts are in chronological order, the Board's most recent statements are at the *end* of attachment A.

Attachment A

The Board's Views on Thermal Loading:
Selected Excerpts from Board Reports and Correspondence
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The Board's Views on Thermal Loading: Selected Excerpts from Board Reports and Correspondence[1]

First Report to the U.S. Congress and the U.S. Secretary of Energy. March 1990.

The Board identified thermal loading as a cross-cutting issue for future inquiry with the following statement:

Even under the best of circumstances, technical uncertainties will persist regarding the performance of any geologic repository. However, the lower the level of uncertainty, the greater the confidence the technical community and the public will have in geologic disposal. When 20-year-old spent nuclear fuel is disposed of in a geologic repository, heat is given off by the spent fuel increasing the temperature of the surrounding rock formations (thermal pulse). Uncertainty about a repository's long-term performance is related in part to this thermal pulse.

Many European countries plan to reduce uncertainties associated with geologic disposal by reducing the thermal loading of the repository. This can be done by: (1) allowing the radioactive material in spent nuclear fuel to decay or "cool" prior to disposal, (2) putting less spent nuclear fuel in each canister (at a planned spacing), or (3) increasing the spacing among waste canisters. For example, the heat output from spent nuclear fuel can be reduced by 30 percent by allowing 20-year-old spent nuclear fuel to age for another 20 years prior to disposal. This issue will require in depth briefings by the DOE and considerable evaluation by the Board. In such a cost-benefit analysis, for example, the benefits gained by reducing the thermal loading have to be balanced against the possible need for additional waste storage facilities, an increase in the number of waste packages, and the need for more repository capacity.

Second Report to the U.S. Congress and the U.S. Secretary of Energy. November 1990.

The Board identified thermal aspects of repository design as concerns with the following statements:

The proposed design of the repository and waste package calls for maintaining the near-field temperature of the waste package above the boiling point of water for 300 years or longer to

[1] This attachment contains excerpts from official Board documents. The sources for this attachment were all Board reports, all Board correspondence, including correspondence to OCRWM giving feedback from Board meetings, and one letter to Lake Barrett setting the agenda for the June 1999 meeting in Beatty. All of the sources are on the Board's website. Report/correspondence titles are in bold print. Introductory statements are italicized. Excerpts from the Board reports/correspondence are in regular type and are verbatim. The attachment is limited to statements about thermal loading (i.e., about the relationships between repository temperatures and repository performance and understanding). If similar statements appear two or more times in the same report, only one is excerpted for this attachment. If a statement in a Board report/correspondence is subsequently duplicated in later reports/correspondence, such duplications are not included here. In several cases, to improve readability, the excerpted statements from a report do not appear in the same order as in the original report.

drive any groundwater away from the waste packages, thus minimizing the potential for corrosion. At the same time, temperatures would be kept low enough to avoid potential degradation of the waste package and the geologic barriers.

The Board feels it is essential to understand the relative merits of alternative repository configurations and designs especially the factors influencing the thermal loading on the repository host rock and the Calico Hills nonwelded tuff. Uncertainties persist concerning mineral and permeability alterations, including potential changes in the mineral sorption characteristics of the zeolites that could result from the anticipated thermal loading. A better understanding of the heat-pipe effects that occur when groundwater vaporizes and condenses near the waste packages also is needed.

Third Report to the U.S. Congress and the U.S. Secretary of Energy. May 1991.

The Board continued demonstrating its strong interest in thermal loading with the following statements:

The Board is interested in hearing about research into the potential effects of thermal loading on the repository and the development of engineered barriers.

The Board believes that the technical rationale and conceptual design of the repository, particularly with regard to thermal loading, have not progressed to the same level of definition as that of the ESF. Assumptions have been made about the characteristics and configuration of the repository during the ESF alternatives study that may be shown to be less than valid in the future. The DOE should continue with repository conceptual design throughout the design phases for the ESF. Different geometric layouts and thermal-loading alternatives for the repository should be explored.

Fourth Report to the U.S. Congress and the U.S. Secretary of Energy. December 1991.

Because the Board conducted an important, three-day conference on thermal loading and its relationship to repository design in October 1991, too late for full treatment in the Fourth Report, this report promised full treatment of thermal loading in the Fifth Report.

Fifth Report to the U.S. Congress and the U.S. Secretary of Energy. June 1992.

The principal topic of this report was thermal loading:

[T]he thermal-loading strategy chosen for a geologic repository will affect most other components of the system, including decisions about ageing, the repository size and design, the design of the waste package, as well as decisions about how the spent fuel will be stored and transported.

The specific details of the DOE's proposed thermal-loading strategy appear to have evolved incrementally over the last two decades, and a number of conditions have been assumed. Important documents relating to the evolution of the U.S. program clearly suggest that the DOE has always assumed high thermal loads for repositories in this country, regardless of the disposal environment. A comprehensive and systematic analysis of alternative, and potentially better, thermal-loading strategies (e.g., below-boiling temperatures, or above-boiling temperatures for 10,000 years or more) for the proposed Yucca Mountain site has not yet been completed. As a result, a firm scientific and technical basis for the DOE's current baseline thermal-loading strategy for the Yucca Mountain site does not exist.

An important hypothesis behind the [current, high-temperature] strategy is that a region surrounding the waste packages will dry out for the 300-to-1,000-year period and that liquid water, which could cause container corrosion and serve as a vehicle for the transport of radionuclides to the accessible environment, will not be present. This hypothesis has yet to be tested, however. Because an adequate evaluation of the *technical merits and uncertainties* of various thermal-loading strategies has not yet been performed, the Board believes that making a commitment to a specific strategy and corresponding repository and waste management system design is premature.

Waste disposal must be looked at as a complex, *integrated* system. Thermal-loading decisions control the repository design, which in turn affects how and what decisions are made about other system components — such as the emplacement concept or the waste package design, fuel storage, and transportation. The Board recommends that the DOE thoroughly investigate alternative thermal-loading strategies that are not overly constrained by a desire to rapidly dispose of spent fuel. This investigation should involve a systematic analysis of the *technical advantages and disadvantages* associated with the different thermal-loading strategies. An assessment of each strategy's implications for other elements of the waste management system also should be undertaken.

One of the first reports to focus on uncertainties introduced by high thermal loads is a 1978 report by the U.S. Geological Survey. This report recognized that "...given the current state of our knowledge, the uncertainties associated with hot wastes that interact chemically and mechanically with the rock and fluid system appear very high." The report further concludes: "The uncertainties connected with all these media are greatly reduced if the media are used, at least initially, only for relatively cool waste (surface temperatures < 100°C)."

Finally, the NRC in 1983 established in 10 CFR 60 a 300-to-1,000-year waste package containment requirement. In the accompanying statements of consideration, the NRC expressed its concern that "thermal disturbances of the area near the emplaced waste add significantly to the uncertainties in the calculation of the transport of the radionuclides through the geologic environment." A review of the literature has not uncovered any substantial body of work intended to resolve or reduce the uncertainties associated with high thermal loads. These uncertainties persist today.

If the current thermal-loading strategy (which assumes an above-boiling environment for only part of the regulatory lifetime) is adopted, both above-boiling and below-boiling environments will have to be accounted for. This raises at least two questions: Will the need to characterize two different hydrologic regimes (both changing in time and space) result in a large increase in uncertainty? Will the below-boiling hydrologic regime occurring after extensive heating of the rock be significantly different from the current ambient regime?

The principal minerals that can sorb radionuclides at Yucca Mountain are zeolites (for example, clinoptilite and mordenite) and clays such as smectites. These minerals occur in close proximity to the proposed repository horizon. Modification of their sorptive abilities, as a result of temperature increases, has always been a topic of interest to those concerned with the efficacy of the geologic barrier to isolate waste. Also important is the effect of thermally induced geochemical and mineralogic changes on the flow regime itself. The effects of thermal loading on geochemistry are complex and dependent upon a multitude of factors. If one wants to minimize the complexity, lower thermal loads, which affect smaller rock volumes, are preferred. On the other hand, increased thermal loads would appear to have less of a direct effect on sorption and the retardation of radionuclides than they would on the flow regime itself. Predicting the effects of precipitation and volumetric mineral phase changes on permeability and porosity in a fractured medium will be a difficult problem.

So far, however, a comprehensive examination of the advantages and disadvantages of alternative thermal-loading strategies (e.g., below boiling, or above boiling for several thousands of years) in various media — or at least in tuff — has not yet been undertaken. Recently the Board was told that under the oversight of the management and operations contractor a systems analysis would be performed that planned to consider several thermal-loading strategies. The Board believes that such an effort is overdue.

Both the technical and nontechnical communities could perceive the current above-boiling strategy as entailing greater uncertainties with regard to geotechnical, hydrologic, and geochemical aspects than a below-boiling strategy because many conceptual aspects associated with above-boiling conditions have yet to be tested and validated. Like the current U.S. baseline strategy, the long-term above-boiling strategy could be perceived by the technical and nontechnical communities as entailing more uncertainties than the below-boiling strategy.

The capacity of any repository for spent fuel and high-level waste is directly related to thermal loading. As a result, realistic estimates of the waste disposal capacity of the proposed Yucca Mountain site can be made only after underground exploration has been conducted and a thermal-loading strategy has been confirmed through a balanced combination of modeling and underground testing.

As outlined above, many uncertainties about the current baseline thermal-loading strategy persist. The Board believes that testing the validity of alternative strategies should proceed as soon as possible in parallel with studies of the current baseline strategy. In assessing the different thermal-loading strategies, it is critical that special attention be paid to evaluating the uncertainties and, in particular, the critical hypotheses associated with each strategy. The Board strongly encourages the DOE to review its research plans to ensure that this evaluation be carried out through a balanced combination of modeling, field mapping, laboratory testing, long-term, large-scale underground testing, and, if appropriate, the study of natural analogues. This information could then allow the timely selection of a prudent thermal-loading strategy.

A systemwide study of alternative thermal-loading strategies should be undertaken. Alternative waste package concepts and emplacement modes, backfill, and enhancements for controlling thermal effects in the repository could be considered as part of the repository conceptual design for this study.

Of great significance to the design and fabrication of radioactive waste containers is the choice of a thermal-loading strategy for the repository. And potentially advantageous opportunities could exist if repository thermal loading is shown to be a constructive additional attribute of the engineered barrier system. For instance, it may be desirable to keep the entire repository waste inventory dry for over 10,000 years by "engineering" a relatively high thermal load. Perhaps maintaining consistent conditions at either high or low temperatures will prove most useful for reducing uncertainties about containers lasting "thousands of years." The type of container chosen for emplacement in the repository also will affect to varying degrees many other parts of the waste management system. Research aimed at verifying and optimizing the roles of the various components of the engineered barrier system (including thermal loading) has not yet been carried out. Although this research, which requires time and personnel, is sorely needed, funding in this important area has consistently been cut during the last three years.

Sixth Report to the U.S. Congress and the U.S. Secretary of Energy. December 1992.

The Board continues its strong interest in thermal loading, shows concern about the potential thermochemical effects of refluxing, and urges DOE to conduct underground heater tests, as the following selected statements from the report indicate:

A critical issue discussed was the DOE's theoretical, untested understanding of the magnitude and consequences of repeated evaporation and condensation (i.e., reflux) of moisture in the rock adjacent to the emplaced waste, as well as its significance to the selection of a thermal-loading strategy. It was postulated that reflux of water vapor in the unsaturated rocks adjacent to the emplaced waste will occur under temperature gradients as low as a few tens of degrees. In a low thermal-loading repository, reflux could repeatedly leach the rocks and, with accompanying evaporation, could lead to steadily increasing salinity in the percolating liquid. Such an environment could be corrosive to metal canisters and thereby offer an increased risk of waste package failure and radionuclide release.

The Board believes that to better understand such complex processes, long-term underground heater experiments in unsaturated tuffs are required. These experiments should be designed to establish conditions similar to those expected for low to high thermal loadings. Key unanswered questions that need to be evaluated are (1) the potential for steam corrosion of the metal waste package at temperatures above boiling, (2) the effect of refluxed moisture on rock hydraulic conductivity, and the scale of such effects as a function of the thermal loading. Before the DOE can reliably predict the evaporation-condensation-convection processes postulated for either of the thermal strategies, however, more data are needed. Data needed to characterize the site for either thermal-loading strategy can be obtained only by conducting high temperature testing in welded tuff of the proposed repository geologic formation.

Underground Exploration and Testing at Yucca Mountain A Report to Congress and the Secretary of Energy. October 1993.

This report (eighth in the NWTRB series), is a single-topic report that focuses on the exploratory studies facility: its conceptual design, planned exploration and testing, and excavation plans and schedules. Despite the narrow theme of the report, the Board urges DOE to undertake underground thermal testing as soon as possible to help provide data for thermal loading decisions.

Report to The U.S. Congress and The Secretary of Energy: January to December 1993. May 1994.

In this summary report for all 1993 activities, the high importance of resolving the thermal loading issue is stressed. The Board mentions use of ventilation and extended heat transfer surface for the first time and advises DOE to include these and other heat transfer methods in thermal loading studies. Also for the first time, the Board raises the issue of *extended retrievability* *(keeping the repository open for more than 50 years) as an approach to improving flexibility that may be technically and socially wise.*

Thermal loading — how to plan both for accommodating and using the heat produced during the radioactive decay of nuclear waste in a repository — continues to be a very important, if not the foremost, issue for the repository. Although considerable progress has been made, it is clear that the issue is far from resolved.

The Board is looking forward to the results of this broader repository-level system study. This study is said to be the first total system look at the thermal-loading issue in a repository. It will be interesting to see how the study addresses the practical operating problems that will be common to all thermal-loading strategies. Such problems include determining placement locations for individual waste packages (which may have widely varying heat-generation characteristics) and carrying out a multi-decade program to confirm the long-term performance of emplaced waste packages, which, depending on their design, age, and contents, may or may not have high surface temperatures or emit high levels of radiation.

[R]epository program personnel performed a brief modeling study on the effect of tunnel diameter on waste package temperature for various thermal-loading strategies. Assuming neither backfilling nor ventilation of the tunnel, the study results indicate, as expected, that the smaller the drift, the higher the temperature in a waste package. [T]he difference between peak internal temperatures as a function of drift diameter should…decrease with decreasing thermal loading. How strong this function is, however, depends on design assumptions about how the heat would be spread out in the drift. It is important, therefore, particularly for higher thermal-loading strategies, that the DOE include in its Advanced Conceptual Design phase the examination of drift size, as well as methods for spreading heat out within a drift. An example of a passive method for spreading heat within a drift is the use of extended heat transfer surface on the waste package, the drift walls, or both. Examples of active methods are the use of heat pipes and ventilation or the recirculation of air within a drift.

Extended retrievability means keeping the geologic repository for the disposal of high-level waste open for a finite, longer period than the minimum 50 years required in the regulations. Some potential advantages to extended retrievability in a repository include: (1) ease of monitoring over longer periods, (2) opportunity to implement technological changes, (3) ease of modifying thermal strategies by adjusting waste package spacing, (4) ease of treatment of waste, if desired, and (5) ease of access to waste for future beneficiaries. In a word, extended retrievability means flexibility — a move that may be technically and socially wise.

Report to the U.S. Congress and the Secretary of Energy: 1994 Findings and Recommendations. March 1995.

In early 1994, DOE formally adopted a new ”Program Approach,” which, among other things, seemed to be based on “low” thermal loading and placed increased emphasis on the waste package and on extended retrievability. The Board’s comments on thermal loading in this report follow:

As part of its new program approach, the DOE has concluded that the best possibility for a successful license application includes a baseline thermal management strategy with a “low” thermal load. Flexible designs will be developed for the repository and the waste package. A site…recommendation, and a license application to construct will be made in…2000, and 2001, respectively, assuming that the repository will be operated at a “low” thermal loading. Long-term testing will be carried out to support a possible 2008 application to obtain an operational license to accommodate a higher thermal loading.

Since a clear definition of “low” thermal loading has not yet been articulated, the strategy is preliminary in concept. Its choice as the program approach to thermal management seems to rest mostly on the belief that, because it might be easier to provide bounding and confirmatory analysis for the strategy, the likelihood of achieving regulatory compliance with this strategy is higher than with other strategies. The Board believes that, at this time, insufficient data and analyses are available to make a scientifically and technically based choice of a strategy for the thermal loading of a repository. The DOE needs to define what data and analyses will be needed to support this concept and how the data will be obtained. Finally, for the program approach to be credible, the DOE must clearly define actions that will be taken if a case cannot be made for an amendment to the license prior to 2008 that would allow the repository to operate at a higher thermal loading.

[There are] [s]everal important issues…about which very little knowledge currently exists: (1) Would the large waste packages currently undergoing design be compatible with the “low” thermal management strategy? (2) What ventilation concepts might be useful for removing heat from the repository? (3) What thermal testing would be needed to gain a sound understanding of the “low” temperature thermal management strategy?

Common to all thermal management options is the need to understand the efficiencies that could result from continuing to ventilate the repository after emplacement and prior to closure. It has been postulated that the removal of moist air from the repository could be very beneficial to the “low” options and possibly for operational considerations. It has been postulated that ventilation concepts that continuously remove warm moist air from the repository over the entire preclosure period (i.e., now 100 years) could appreciably reduce the required area. This concept has not yet been evaluated by the DOE…

The program approach to thermal management is preliminary and has not been developed sufficiently to allow its evaluation. The strategy assumes that the areal power density for the repository, as yet undefined, will be sufficiently small such that it can be argued to have a minimal and predictable disturbance on the mountain. The strategy is not based on any belief that a "low" thermal load is better than other strategies or has inherent advantages for waste isolation over another strategy. It is based on the present belief that there is a higher probability of achieving regulatory compliance with this strategy given the current state of knowledge of site processes and the potential response of those processes to increased temperatures.

The effects of waste heat on repository performance must be understood well enough to permit confident predictions of (or bounds on) repository performance for alternative thermal loadings. Current performance assessment calculations cannot resolve differences between the performance of different thermal-loading strategies…A few alternatives for the thermal loading of a Yucca Mountain repository should be carried forward until a better technical basis has been developed for choosing a preferred loading.

[A]n implied assumption is being made that the "low" thermal-loading strategy will result in a longer period of contact between the waste packages and liquid water, and therefore that the waste packages will require an additional outer barrier to attain acceptable performance. This implied assumption depends on yet other assumptions about how the repository is designed and operated, such as the order in which spent fuel is received for emplacement at the repository, the amount of ageing of spent fuel that will take place before emplacement, and the extent and duration of repository ventilation. Implied assumptions should be identified and articulated, so that they may be evaluated and questioned.

Disposal and Storage of Spent Nuclear Fuel – Finding the Right Balance. March 1996.

This was a special report on storage. The only mention of thermal loading was that storage offers the advantage of allowing spent fuel to be mixed and matched to optimize the thermal loading of the repository. The report also mentioned that one prerequisite for determining site suitability was to "[c]ollect initial results from underground drift-scale heater experiments to better predict the movement of water in the rock surrounding the hot waste packages."

Report to the U.S. Congress and the Secretary of Energy: 1995 Findings and Recommendations. April 1996.

This report explored the linkage between thermal loading and thermal testing with the following statements:

Long-term, essentially complete containment depends strongly on the in-tunnel environment, both during and after the heating episode, and the types of materials best suited for that environment. *Predicting and verifying the long-term, in-tunnel environment remains a challenge.* In-situ thermal testing is the best way to provide some data on the importance of the interactions between thermal, hydrological, and chemical processes.

The Board supports initiation of a long-term, tunnel-scale thermal test as soon as possible and recommends that more thought be given to how more information can be obtained from all heater tests. A short-term thermal test will not provide the information required to influence an early site-suitability decision. The most useful testing will be the in-situ long-term heating experiment, probably during a significant part of the preclosure period, to develop confidence in the long-term predictive capabilities.

A substantial degree of control of container temperatures is possible by engineering design, e.g., by varying the spacing among containers, by using conducting or insulating materials outside the containers to affect heat transfer, by forced or natural cooling (ventilation or natural convection), or by ageing the wastes.

Report to the U.S. Congress and the Secretary of Energy: January to December 1996. March 1997.

The period covered by this report was an extremely challenging one for the project. Reacting to budget cuts and Congressional pressure for visible progress, DOE invented a new near-term product, the VA (Viability Assessment), to be delivered on September 30, 1998. In the thermal loading area, the Board continues to express its strong belief on the need to evaluate repository design alternatives and to carry out appropriate thermal tests:

The issue of the appropriate repository thermal loading has long been of concern to the Board. Areal thermal loading…has a direct effect on almost all aspects of the design and safety of the repository.

Early in fiscal year 1995, the DOE directed repository designers to proceed assuming a high thermal-loading (high-temperature) strategy but not precluding the option to revert to a lower thermal load if test data invalidate the use of the high-temperature regime. Since the DOE's decision…to proceed…with a high thermal-loading strategy, little progress has been made in evaluating alternative strategies for repository thermal management. For example, evaluations have indicated that a low-temperature repository (all rock temperatures below boiling) could be designed without increasing the current area if the repository is ventilated continuously and lower maximum thermal output is assumed for the waste packages.

Several years ago, the DOE assembled a single set of design assumptions that did *not* include alternatives… Now, any consideration of alternatives is treated as an "add-on" modification to the existing design. Not surprisingly, when alternatives are investigated as add-ons to the existing design rather than as features of designs that are integrated with the alternatives, they often are found to be prohibitively expensive. A credible analysis should be made of design alternatives…that may lead to fundamentally different repository designs. "Force-fitting" alternatives onto an existing design with which they may be incompatible is not an effective way to evaluate their merits.

The Board believes that alternative concepts for underground operations should be developed and examined. This should begin immediately so that any alternatives that appear feasible and practical may be considered in the VA. At least one of the alternatives should be based on conservative application of existing technology, for example,…ventilating the emplacement tunnels to provide temperatures low enough for effective functioning of humans and machines, sensors, and other equipment. Ventilation may help to remove water from the repository, rather than having it condense above and later percolate down through the repository. Ventilation also may reduce thermal effects in the repository.

[T]the DOE adopted an approach to repository design, called the "focused development approach," in early 1994. A hallmark of this approach is moving forward with a single design for the underground and surface parts of the repository and for the waste package. The focused development approach is risky because there is no fallback position if the single design being pursued turns out to be marginal or unacceptable. This is especially the case if the assumptions supporting the design (e.g., a dry repository) turn out to be unsupportable.

Report by letter to the Secretary of Energy and the Congress. December 23, 1997.

[T]he Board believes that the DOE should develop viable alternatives to its current reference repository and waste package designs. An important consideration associated with designing the repository and the waste package involves understanding how elevated temperatures within the repository caused by heat generated by the spent fuel will affect the waste packages and the rock surrounding the waste packages. Because of the importance of the "thermal load" for repository and waste package design, we are pleased to note that the drift-scale thermal testing facility at the site was completed ahead of schedule and that thermal tests began there in early December.

January 12, 1998, letter to Lake Barrett [feedback from the October 1997 meeting]

With this letter the Board began the practice of sending a letter to the (acting) Director of OCRWM after each Board meeting giving feedback from the meeting. The Board adopted the new practice partially in response to OCRWM concerns that information in "official" Board reports often was not timely.

The design options discussed at the Board meeting appear to involve "add-ons" (e.g., drip shields) to the existing reference designs. In addition to evaluation of design add-ons, we believe the program would benefit from serious study of other repository and waste package designs that represent alternatives to the reference designs. Examples of design concepts that could be explored include some or all of the following: (1) a design in which the boiling fronts do not coalesce between drifts; (2) a design permitting humans wearing typical work clothing to safely enter emplacement drifts containing waste packages to inspect, maintain, retrieve, or emplace them; (3) a design with a smaller emplacement-drift diameter (e.g., 3.5 meters) and simpler ground support; (4) a design using preclosure or postclosure ventilation or both, based on natural convection, forced convection, or a combination of both; and (5) a waste package design using two corrosion-resistant materials. Each concept for repository design should address all thermal constraints *and* accommodate at least 70,000 metric tons in the current repository footprint. In any case, the repository design should take advantage of the density difference between the warm exhaust air and the cooler intake air to maximize preclosure heat removal by natural convection.

The Board believes that including alternative repository and waste package designs in the VA is a good idea, although it is clear that alternatives will not be as fully developed as the reference case. In particular, we think it is vital that the VA that is conveyed to Congress includes alternatives that show an array of cost-versus-performance choices.

[S]everal members of the Board had the opportunity to look over the drift-scale thermal test facility during their December 4 tour of the ESF. The Board is very pleased that drift-scale thermal testing has begun and considers the planning, design, construction, and start-up of the facility in less than two years a remarkable accomplishment. We share in the hope that the facility will provide valuable data for increasing understanding of the implications of various thermal loads for repository and waste package performance.

1997 Findings and Recommendations. April 1998.

This was the first full report of the "new" Board, chaired by Jerry Cohon. In the thermal loading area, the Board again commended DOE for the drift scale heater test. The Board also advocated study of alternative repository designs for the VA, mentioning particularly the use of ventilation to lower temperatures.

The data from [the drift scale heater] test will substantially improve our understanding of thermal response. The DOE is commended for planning and constructing this facility.

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

The Board is very interested in seeing serious study of alternative repository designs. Such designs must treat the entire repository as an integrated system. The Board believes that these design concepts can be developed in a way that allows meeting all thermal constraints while retaining the current design's capability to dispose of 70,000 metric tons of high-level waste and spent fuel within the current repository footprint. Although it is neither necessary nor appropriate that the alternatives be developed as fully as the reference design at the time the VA is delivered, we believe that including alternative design concepts in the VA could enhance the VA's value and credibility significantly. Thus, we urge the DOE to consider including alternative design concepts in the VA. The Board believes that alternative design concepts can be identified, developed, and included in the VA without delaying the VA.

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

July 30, 1998, letter to Lake Barrett [feedback from June 1998 meeting]

Alternative Repository Designs. Michael Voegele presented a plan for examining alternative configurations before selecting a repository design that the OCRWM will carry forward to site recommendation and license application. The Board is pleased that the OCRWM has made this commitment. The Board is concerned, however, that, according to budget figures available to it and the current level of project activities, this examination may not be as comprehensive as the

Board believes it ought to be and that it might not be completed in time to play a meaningful role in the May 1999 design decision. The Board reemphasizes the importance it attaches to a full-scale systems engineering analysis. Such an analysis should evaluate alternative system concepts incorporating various combinations of repository and waste package features, including, but not limited to, restricting peak temperature to below 80° C, long-term ventilation, and the location of the corrosion-resistant layer in the waste package design.

Report to the U.S. Congress and The Secretary of Energy. November 1998.

Internally, the Board referred to this report as the "Roadmap" because its intial purpose was to delineate the critical research necessary for a site recommendation decision. The Board published this report shortly before DOE's December 1998 issuance of the VA. In the thermal loading area, the Board again stresses the uncertainty of the current, hot, design, and urges examination of cooler alternatives.

*Thermal Loadin*g. Radioactive decay of wastes generates heat, which would have pervasive but uncertain effects throughout the repository, particularly during the first several centuries after waste emplacement. The layout of the repository, the extent of ventilation, and the mix of waste packages all affect the "thermal loading," or extent of heating, in the repository. Above-boiling temperatures affect water flow through the UZ in ways that are complex and difficult to predict. Heat also affects chemical reactions, including those that influence the waste package environment and the rate of waste package corrosion. Expansion of rocks as they heat up and contraction later as they cool down may affect tunnel stability and hydrologic properties.

The effects of repository heat on thermohydrologic conditions near the repository are not well understood, but tests have been initiated at Yucca Mountain to improve understanding and reduce uncertainties. If the repository is designed for above-boiling temperatures, there may be additional water movement around, and perhaps into, the emplacement tunnels when temperatures are high. The rocks of the repository horizon, although not fully saturated, contain a significant volume of water. As temperatures in the host rock rise above the boiling point, this water will be vaporized in the rock pores and move within fractures toward cooler, below-boiling regions. There, the vapor will condense and migrate downward from the point of condensation. The consequences of this complex, transient, and episodic hydrologic process are difficult to predict, resulting in significant uncertainty about the environment for the waste packages.

A repository should be designed to reduce the importance of potentially negative interactions among some of its components. For example, smaller-diameter tunnels would be more stable than larger-diameter tunnels, reducing uncertainty about the effects of rockfalls on the waste package environment. Another example is the thermal loading of the repository. If the temperature rise can be limited (e.g., by ventilation, through aging of wastes, or by other means), there would be less disturbance of the hydrologic, mechanical, and chemical conditions in rocks surrounding the repository tunnels. The objective of changing the repository design from its current configuration would be to create a more predictable and less corrosive environment for the waste package.

Criteria for evaluating alternative features and design concepts have not been clearly defined yet, and the schedule established by the DOE for their evaluation may be difficult to meet. The evaluation should be framed around the overall objective of reducing uncertainties in performance. It might include a reexamination of key self-imposed geologic constraints and design assumptions, including minimum thickness of rock cover, minimum offset from faults, minimum distance from zeolite-rich strata and from the water table, and selection of the substrata in which emplacement tunnels are to be located.

Alternative repository and EBS designs could improve waste isolation or reduce uncertainties in projections of repository performance. A thorough evaluation of alternatives is needed. Over the next several months, the DOE intends to evaluate alternative features and design concepts that may enhance performance or decrease uncertainty. Among the more important alternatives to be evaluated are lower-temperature designs that use ventilation to reduce uncertainties about the heat-induced hydrologic, mechanical, and chemical changes in the rock surrounding waste emplacement tunnels.

The current design of the underground facility reflects a 1995 study and a DOE decision to focus on designs with high areal mass loading. The decision resulted in large part from the hypothesis that the heat from the decay of the radioactive waste could provide an above-boiling environment for waste packages for up to thousands of years and that such an environment would result in low humidity, low waste package corrosion, and therefore low waste package failure rates. However, water that vaporizes in the rock would condense in cooler regions of rock farther away, and some of this condensate could flow back onto some of the packages. The resulting hot and wet conditions could exacerbate waste package corrosion and mobilization of radionuclides in the waste. (Such "refluxing" of condensate could be of particular concern if waste package materials are susceptible to pitting corrosion at temperatures marginally below boiling.) In addition, as the underground facility eventually cools and waste package temperatures fall below boiling, hot and wet conditions can be expected. Uncertainties about how hydrologic and mechanical conditions in the surrounding rock will evolve over time make it difficult to predict the waste package environment and, thus, the ability of the waste packages to contain radioactive waste.

Evaluations of alternative underground facility designs are needed, especially those that may provide at least the same level of performance with reduced uncertainty. Many aspects of underground facility design may affect performance, including tunnel diameter, waste emplacement mode (e.g., in tunnel openings, walls, or floors), degree of ventilation, and use of backfill or drip shields.

One of the most important aspects of design is repository temperature. A cooler design may have the advantage of greater certainty about the hydrologic and mechanical behavior of the rock surrounding tunnels and could reduce the rates of waste package corrosion and radionuclide mobilization from the waste. Lower peak temperatures also would reduce the degree of coupling between the thermal and the hydrologic, chemical, and mechanical processes—a major source of uncertainty in estimating performance. Lower temperatures could extend waste package life by preventing (or at least reducing) the period when conditions are both hot (near boiling) and wet—conditions known to exacerbate corrosion of waste package materials.

Underground facility temperatures may be reduced by aging the spent fuel before placing it in the underground facility, by using smaller waste packages and placing them farther apart to reduce the areal mass loading, by continuously ventilating the waste emplacement tunnels before underground facility closure, or by a combination of the three procedures. A cooler underground facility design could use ventilation to keep the walls of emplacement tunnels below boiling, thereby reducing the degree to which water vaporizes near the wastes and moves to cooler regions where it would condense. Removal of heat by ventilation also would permanently remove some water through evaporation into the normally very dry desert air. By limiting temperatures, this design would simplify predictions of hydrologic, mechanical, and chemical conditions in nearby rocks. There may be offsetting disadvantages of increased ventilation, more-complex fuel-aging procedures, or increased repository area. Analyses of alternative designs should illuminate the relative merits of hot and cooler designs.

March 3, 1999, letter to Lake Barrett [feedback from January 1999 meeting]

Repository Design. The Board members were very pleased that the first LADS workshop encouraged the advocacy teams for competing designs to think well beyond the bounds of previous repository design concepts. The Board believes that the selection criteria and weighting must be clearly defined and that the transparency of the process should be improved. As you noted at the Board meeting, the VA reference design will undergo evolutionary change as a result of the LADS process. However, the Board reiterates that an analysis of alternative repository designs should not be simply an evaluation of "enhancements" to the reference design. In particular, high temperatures in the VA reference design lead to large uncertainties about how the site would behave both before and after closure. *Therefore, the Board believes that the DOE should give serious consideration to true alternatives to the reference design, including changing from a high-temperature to a ventilated low-temperature design.* The Board believes that a repository design based on lower waste package surface temperatures could significantly reduce uncertainty, enhance licensability, and simplify the analytical bases required for site recommendation.

Some of the factors that have influenced the Board's thinking on repository design follow.

- *Corrosion severity would be significantly reduced by lowering waste package temperatures.*
- *There would be degradation of tunnel stability because of the thermal pulse.*
- *There would be significant reduction of coupled thermal-hydrologic and thermal-geochemical processes at lower temperatures.*

The Board recommends that a more complete quantitative analysis of a low-temperature repository design be undertaken before the completion of the LADS process. For example, preliminary calculations could be performed in the next several months to quantify the removal of heat and water from continuously ventilated repository tunnels. Such an evaluation also should include an analysis of the long-term stability of the tunnels.

The Board reiterates that a repository design based on lower waste package surface temperatures has the potential to reduce uncertainty, enhance licensability, and simplify the analytical bases required for site recommendation. Through additional analysis and clear selection criteria, this potential alternative could be reasonably compared with the VA reference design or other variations of the VA design.

Report to the U.S. Congress and the Secretary of Energy: Moving Beyond the Viability Assessment. April 1999.

This short (11- page) report was the Board's review of DOE's December 1998 Viability Assessment. It essentially repeats, in capsule form, what the Board said in its November 1998 "Roadmap." Perhaps the most revealing sentence in this report regarding the Board's thoughts about low-temperature designs is the following: "The Board strongly urges that serious consideration be given to alternatives that keep waste package surface temperatures below the boiling point of water."

[T]he Board believes that the DOE should give serious consideration to alternatives to the VA reference design, including changing from a high-temperature design to a ventilated low-temperature design (e.g., below the local boiling point of water).

[S]uch site characteristics as the movement of water in liquid and vapor forms at temperatures above boiling and the effects of high temperatures on rock stability are important only because of the VA's high-temperature repository design. In a low-temperature design, uncertainties about these phenomena would be less significant and might not need resolving before making a suitability determination.

[T]he Board concludes that a significant amount of additional scientific and engineering work will be needed to increase confidence in a site-suitability determination…The DOE should evaluate alternative repository designs that have the potential to reduce uncertainties in projected repository performance, thereby reducing the scope of additional necessary scientific study.

Regardless of the design adopted, long-term scientific studies will be needed to establish a solid foundation for projecting repository performance…

Uncertainties also are associated with specific characteristics of the Yucca Mountain site, especially the nature of water movement through the fractured unsaturated rocks of the mountain and the possible entry of water into repository tunnels and its contact with waste packages. Many of these uncertainties likely would be exacerbated by the high temperatures of the reference repository design…The substantial uncertainties about the performance of a repository that is based on the VA reference design can be resolved only by considering alternative repository and waste package designs and by collecting additional scientific data.

High temperatures in the VA repository design cause large uncertainties about how the site would behave both before and after repository closure. The Board believes that repository designs with lower waste package surface temperatures merit further detailed analyses. Such designs have the potential to reduce uncertainty, simplify the analytical bases required for site recommendation, and make licensing easier,

The following factors influenced the Board's thinking on repository design.

- Lower temperatures would significantly reduce the uncertainty associated with coupled thermal-hydrologic and thermal-geochemical processes. Maintaining near-field temperatures below the boiling point of water after repository closure, by ventilation or through aging, could reduce uncertainties about the movement of water and associated geochemical processes in the repository's natural barriers. This could increase confidence in the analyses of repository performance required for a site-suitability determination.
- For a given environment, the chances of degradation of corrosion-resistant waste package materials would be reduced significantly if peak waste package surface temperatures were reduced.
- High repository temperatures are expected to increase the mechanical degradation of repository rocks. There is little, if any, relevant experience to draw on for predicting the long-term effects of repository heating and subsequent cooling on drift stability

The Board strongly urges that serious consideration be given to alternatives that keep waste package surface temperatures below the boiling point of water.

Report to the U.S. Congress and the Secretary of Energy. April 1999.

The report again emphasizes the uncertainty associated with the "hot" design and urges DOE to examine cooler, ventilated designs.

The effects of repository heat on thermohydrologic conditions near the repository are not well understood.

In the hot repository design, rock temperatures would peak about 50 years after waste is emplaced. If closure of the underground facility were delayed for about 300 years, the temperatures of the tunnels would have decreased to around 120°C and the rock would have passed through its period of maximum thermal response. By then, if the rock were still stable, it likely would remain stable indefinitely, barring significant seismic activity. If it has failed, repairs might be possible before closure of the underground facility.

At the June [1998] Board meeting, the M&O reported on plans for a major alternative repository design study, which is scheduled to produce a preferred repository design by mid-1999.

During 1998, the Board focused its efforts on encouraging the DOE to examine a range of alternative repository designs and conduct trade-off analyses before selecting any one of them. Although the DOE had to adopt a "reference design" early in the VA process and believed that it could not undertake a comprehensive assessment of alternative designs at the same time that it was preparing the VA, the DOE made a commitment to the Board that it would seriously explore other designs before taking one forward into the site-suitability process.

Evaluations of alternative concepts for underground facility design are needed, especially of concepts that may provide the same level of performance but with less uncertainty than provided by the current underground facility design. For example, a ventilated repository design with lower peak temperatures could reduce current uncertainties about the heat-induced, mechanical, and chemical changes in the rock surrounding tunnels and could reduce the rates of waste package corrosion and radionuclide mobilization from the waste.

May 7, 1999, letter to Lake Barrett [prelude to the June 1999 meeting]

This was not a feedback letter from a Board meeting; rather, it was an agenda-setting letter for the upcoming Beatty meeting.

[A]t the time of a suitability determination, large uncertainties will remain about key elements of the natural system. Of particular significance will be uncertainties about the effects of heat from the waste on repository performance. [T]he Board has urged the DOE to evaluate alternative repository designs—especially designs with below-boiling temperatures that may have the potential to reduce some key uncertainties related to waste isolation. Selecting a design that appropriately balances reduction of uncertainty against cost, flexibility, and other aspects of the design is the most important decision the program will need to make in the near future. Because the Board thinks the repository design affects confidence in the suitability decision to be made in 2001, we would like to make this subject a central topic of our June 29-30 meeting in Beatty, Nevada.

The DOE's M&O contractor has completed evaluating several repository design alternatives and is preparing to recommend adoption of one of those alternatives as the preferred design. Because of the importance of repository design to site suitability, the evaluation and selection process should be well founded, well documented, and easily understood by the technical community and the public. At the Beatty meeting, we would like to review the process that the M&O used to evaluate design alternatives and to select a preferred design. We are most interested in learning how scientific uncertainty and opportunities to reduce uncertainty were weighed against other factors during the design selection process.

July 9, 1999, letter to Lake Barrett [feedback on design from June 1999 Board meeting]

During the last 10 months, the…M&O has been studying alternative repository designs for the proposed repository site…This study resulted in a recommendation by the M&O for a repository design. The Board understands that you will decide soon whether to accept, reject, or accept with modifications the M&O's recommended design. High temperatures associated with the repository design used in the *Viability Assessment* issued in December 1998 create large and significant uncertainties about long-term repository performance. The Board believes that lower-temperature, below-boiling, designs have the potential to reduce the uncertainties as well as to simplify the analytical bases required for the Secretary's decision planned for July 2001 on whether to recommend the site for repository development. The Board does not believe that its role is to endorse a particular repository design. In this letter, the Board comments on the process for selecting the repository design and on the recommended design.

The analytical process supporting the M&O's design recommendation was elaborate and resource-intensive. [T]his level of attention was appropriate because of the importance of repository design for the Secretary's site recommendation and for possible subsequent licensing. Because repository design has been considered a key issue by the Board for a long time, we are pleased that the study of alternative repository designs was undertaken. The design recommended by the M&O shows much progress when compared with the design in the *Viability Assessment.*

The M&O's analysis of alternative designs was necessarily based on many assumptions. An important consequence of these assumptions was that many of the alternative designs had long periods with tunnel-wall temperatures above boiling after closure of the repository. Because of the potentially significant effects of these assumptions on repository behavior, their rationale and justification need to be carefully considered, well-grounded, and well-documented. Selecting one design from several alternatives in the face of multiple and conflicting criteria necessarily requires value judgments. The M&O chose not to quantify or otherwise state explicitly the value judgments it used for recommending EDA-II. Because the values are not explicit, the Board — or anyone outside the process — cannot fully understand and evaluate the considerations applied in the selection. Therefore, the Board urges the DOE to be as explicit and quantitative as possible about its evaluation basis for deciding whether to accept the M&O's recommendation.

The Board realizes that issues such as operational flexibility, cost, and worker safety are important considerations in public policy: thus our emphasis on making explicit the values associated with the evaluation of these criteria. In addition, important policy choices — for example, how long the repository should remain open — currently are embedded in the evaluation process used by the M&O to reach its recommendation. These policy choices and their implications for predicted performance of alternative designs should be made explicit.

[T]he Board is most concerned about the technical defensibility of the repository system's design. The Board believes that understanding and quantifying uncertainty is central to the credibility of estimated repository performance, upon which many of the other criteria depend. Repository design has a profound effect on the cumulative uncertainty about long-term repository performance. Thermal loading has a larger effect than any other single design attribute.

In the recommended design, tunnel-wall temperatures would quickly increase to about 160ºC shortly after repository closure and would remain above boiling for more than 300 years. According to present theory, during this high-temperature period, water in the rock near the tunnel walls would vaporize and migrate to cooler areas between the emplacement tunnels, where it would condense and drain. Unfortunately, the understanding of water mobilization and migration processes and effects during this initial high-temperature period is still far too limited to engender a reasonable degree of confidence. Some insight into thermohydrologic response has been gained from in situ thermal tests…However, important results from the drift-scale heater test will not be available for several more years, precluding their use in the context of a site-recommendation decision.

In general, the cooler the repository, the lower the uncertainty about heat-driven water migration and the better the performance of waste package materials. An important temperature for water migration is the boiling point of water. Above this temperature, technical uncertainties tend to be significantly higher than those associated with below-boiling conditions. For the most part, cooler repository conditions also tend to lead away from regimes where waste package materials are vulnerable to severe corrosion. Considering the current uncertainties created by high repository temperatures, the Board does not believe that a strong-enough technical basis exists at this time to support adequately any above-boiling repository design. To use an above-boiling design as the basis for a site recommendation would require a significant gain between now and the time of site recommendation in the understanding of thermohydrologic processes and their effects on materials behavior.

The Board believes that many of the above-boiling designs studied by the M&O, including the M&O's recommended design, could be modified to achieve a below-boiling design simply by increasing the rate or the duration, or both, of ventilation before repository closure. A design modified to achieve below-boiling temperatures would significantly reduce existing technical uncertainties about the long-term performance of the repository, while maintaining the flexibility to go to higher temperatures later if future data and analyses…justify such action. Therefore, the Board urges the DOE to analyze carefully the implications of these and any other possible modifications that might be used to maintain below-boiling repository temperatures.

March 20, 2000, letter to Ivan Itkin [feedback from January 2000 Board meeting]

Repository Design. One way to address uncertainties is to reduce them through modifications of repository design, although uncertainties can never be entirely eliminated. In its July 9, 1999, letter, the Board stated that it ". . . does not believe that a strong-enough technical basis exists at this time to support adequately any above-boiling repository design." The Board suggested that many of the above-boiling designs studied by the management and operating (M&O) contractor could be modified to achieve below-boiling conditions by aging the spent fuel or by increasing the rate or the duration of ventilation before repository closure. In its response to the Board's letter, the DOE committed to examining uncertainties associated with coupled thermally driven processes, to refine models that are the basis for evaluating thermal conditions, and to evaluate design options for increasing the efficiency of hest removal prior to repository closure. We look forward to reviewing the results of these very important efforts and discussing them with you as soon as they become available.

[T]he evaluation of repository design alternatives (including above-boiling and below-boiling design options) using performance assessment models may cause above-boiling designs to appear to have greater certainty about performance than they really have. Adoption of a below-boiling design could substantially reduce most concerns about coupled processes.

Report to the U.S. Congress and the Secretary of Energy. April 2000.

For the first time in one of its "official" reports (as opposed to a letter to DOE), the Board flatly states that it does not believe that a strong-enough technical basis exists…to support adequately any repository design with postclosure rock temperatures above boiling. Furthermore, the Board goes beyond this statement to assert that it is doubtful that the work planned and underway could yield sufficiently better understanding in the next two years to establish an adequate technical basis for making a site-recommendation decision based on any above-boiling design.

In the Board's view, a credible technical basis does not exist for the repository design described in the *VA*. High temperatures in the *VA* repository design would cause large uncertainties about how the site would behave both before and after repository closure. The Board therefore recommended that the DOE evaluate alternative repository designs having lower temperatures of the waste package surface and the tunnel walls. Such designs have the potential to reduce uncertainty, simplify the analytical bases and models required for site recommendation, and make licensing easier. Although the Board has some concerns about the study that the DOE subsequently conducted, it is pleased that the DOE has moved toward implementing a lower-temperature design.

In 1999, the LADS study continued, at an expanded scale of effort, evaluations of design alternatives that took place during preparation of the *V*A. After additional analyses, the DOE announced its adoption of a design having some key features that are significantly different from those of the *VA* design. In particular, the current design uses modest amounts of ventilation for periods of 50 years or more, compared with essentially no ventilation in the *VA* design. The current design uses a waste package with Alloy 22 on the outside of the waste package rather than on the inside as in the *VA* design. The current design also uses a drip shield…The LADS study repository design depends on the assumptions that waste packages can be placed as close as 100 mm apart and that blending will be used to ensure that the peak waste package heat output at time of emplacement would be no greater than 11.8 kilowatts (kW).

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

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

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

June 16, 2000, letter to Ivan Itkin [feedback from May 2000 Board meeting]

[T]he variations with temperature of uncertainties in generalized and localized aqueous corrosion rates of waste-package and drip-shield materials must be determined over the temperature range from ambient to at least the boiling point of water that contains highly concentrated dissolved salts.

Ric Craun's presentation suggested that the current repository design contains sufficient flexibility to allow for changes in repository design as new data are acquired. The chart he presented, which related ventilation time, "staging" time, and distance between waste packages to repository temperature, was very helpful. We agree that there is a great deal of operational latitude in the current design. In particular, the chart clearly shows that broad flexibility exists to implement the design as either a below-boiling or an above-boiling repository. The Board notes, however, that even more flexibility might be available if certain factors now held constant (e.g., spacing between drifts, age of fuel when received at the repository, ventilation efficiency) were allowed to vary.

August 31, 2000, letter to Representative Joe Barton [responses to questions posed by Mr. Barton in a July 20, 2000, letter to the Board following Debra Knopman's appearance before the Subcommittee on Energy and Power on June 23, 2000.]

On the basis of information it has reviewed to date, the Board believes that the technical basis for DOE's current long-term projections of repository performance has critical weaknesses. These projections and their associated weaknesses reflect in part the DOE's "base-case" (above-boiling) repository design. Although the site may, in fact, merit a positive site recommendation, DOE has not yet demonstrated — for the base-case design — a firm technical basis for that conclusion.

Some of the current large uncertainties about waste package and repository performance are directly or indirectly related to the high (i.e., above-boiling) repository temperatures associated with DOE's current base-case design. High temperatures increase the level, extent, and significance of the combined, or "coupled," effects of thermal, hydrologic, mechanical, and chemical processes. Furthermore, the waste packages may be more vulnerable to corrosion at higher temperatures if water is present. The Board believes that it will be very difficult for the DOE to improve substantially its current understanding of these high-temperature effects during the next year or two. However, it may be possible over the next several months to reduce some uncertainties, for example, by developing a defensible technical basis for a lower-temperature repository design.

In addition to the effects of high temperatures, some uncertainties are related to a lack of fundamental understanding about physical processes that will extend over thousands of years; realistic predictions are therefore very difficult to make. For example, the performance of the waste packages over thousands of years has been extrapolated from a few years of corrosion data and too limited an understanding of fundamental corrosion processes.

The Board believes that significantly improving the fundamental understanding of these natural features and engineered barriers during the next year or two will be very difficult. However, the Board believes that work in these areas is important and should continue. Because of the complexity of the Yucca Mountain site and the challenges involved in extrapolating data over long time periods, gaining such an understanding of these basic processes will take time. Continued adequate funding of these long-term studies will be important.

The persistence of substantial uncertainties has led the Board over the last few years to recommend strongly that DOE develop a more technically defensible basis for making design, site-recommendation, and licensing decisions. In particular, the Board has recommended initiation of fundamental studies on long-term corrosion, evaluation of alternative repository designs…Although the Board is encouraged by the level of attention DOE is now giving to the quantification and characterization of uncertainty in estimating repository system performance, the Board also continues to have concerns in this area.

The timing of the site recommendation, of course, is clearly beyond the Board's charge. [T]he Board believes that the technical basis for DOE's current long-term projections of repository performance has critical weaknesses. These projections and their associated weaknesses reflect in part the DOE's base-case (above-boiling) repository design. The Board explicitly raised this concern about above-boiling repository designs in a July 9, 1999, letter to DOE's Office of Civilian Radioactive Waste Management. Although the site may, in fact, merit a positive site recommendation, DOE has not yet demonstrated — for the base-case design — a firm technical basis for that conclusion.

Adopting a lower-temperature repository design for commercial spent fuel might mitigate some of the weaknesses associated with projections of long-term repository performance, such as problems associated with coupled processes. A lower-temperature repository design could make projections of performance less dependent on areas where scientific understanding is incomplete. Therefore, DOE should augment its current design evaluations with a rigorous and persuasive evaluation of the performance of, and trade-offs associated with, alternative repository designs, including assessing the effects of the following factors on performance and uncertainty: age of waste at emplacement, spacing between waste packages, ventilation rates and efficiencies, and time before repository closure. It is possible, but not certain, that a cooler, drier, and simpler design than the current base-case design would lower the technical hurdles that DOE now faces in projecting long-term waste package and repository performance. DOE, however, has not yet carried out a sufficiently thorough evaluation of low-temperature repository designs. By carrying out such an evaluation, DOE would develop a much better understanding of how the thermal characteristics of different designs may affect critical uncertainties (e.g., those associated with coupled processes, the stability of the passive layer of Alloy 22, and the waste package environment). But the magnitude of other uncertainties, such as those associated with the saturated zone under the repository, are very likely to be independent of the facility's design.

For DOE to make a positive site recommendation, the Board believes that DOE would need to make a technically defensible argument that at least one repository design concept, including firm operational assumptions, will perform satisfactorily for thousands of years. Such an argument would presumably consider the associated levels of uncertainty in repository performance. Therefore, the Board assumes that DOE would describe for the site recommendation at least one design concept and a set of operational assumptions with sufficient specificity so that sound and complete assessments of performance can be developed.

[A]lthough the Board noted in July 1999 that the technical basis supporting any above-boiling repository design was…not strong enough, the Board is not in a position to *recommend* a specific design alternative. In fact, in its June 23, 2000, testimony before the Subcommittee, the Board explicitly stated, "… more thorough analysis is needed before any judgment is made about the optimal thermal conditions for repository operation."

[A]t the Board's meeting in May 2000, DOE presented some preliminary results and cost estimates related to alternative thermal designs. That analysis suggested that the incremental discounted cost of implementing a below-boiling (as opposed to an above-boiling) design may be as low as $600 million. If, for example, different assumptions were adopted about the distance between repository tunnels, the incremental cost might be reduced even more. This type of result, stimulated by a Board recommendation, is likely to help DOE understand better the technical and economic trade-offs associated with alternative repository designs.

September 20, 2000, letter to Ivan Itkin [feedback from August 2000 Board meeting; also contains a copy of the Board's August 31, 2000, responses to questions from Congressman Joe Barton]

[T]he Board believes that the technical basis for current long-term projections of repository performance has critical weaknesses. These projections and their associated weaknesses reflect in part the DOE's "base case" (above-boiling) repository design. Although the site may merit a positive recommendation, the DOE has not yet demonstrated—for the base-case design—a firm technical basis for such a conclusion. [S]ome of the current large uncertainties about waste package and repository performance are directly or indirectly related to the high (i.e., above-boiling) repository temperatures associated with the current base-case design

Letter Report to the U.S. Congress and the Secretary of Energy. December 2000.

This very brief (2 pages) letter report contains the following statement:

In the Board's view, the DOE has not yet demonstrated a firm technical basis for its present high-temperature "base case" repository design. The Board looks forward to the results of DOE work that is under way to evaluate the effects of alternative lower temperature repository designs on repository and waste package performance.

March 30, 2001, letter to Lake Barrett [feedback from January 2001 Board meeting]

As you will recall, at the beginning of the meeting, I [Jared Cohon, Board Chairman] read into the record a statement of Board priorities. I noted that the Board "… has recommended that DOE focus significant attention on four priority areas dealing with managing uncertainty and coupled processes, which, in the Board's view, are essential elements of any DOE site recommendation."

> "(3) An evaluation and comparison of the base-case repository design with a low-temperature design;"

The Board is interested in obtaining an evaluation and a comparison of the base-case, high-temperature repository design with a low-temperature, ventilated design. Evaluating a possible low-temperature, ventilated design could clarify the advantages — and disadvantages — associated with keeping waste package temperatures below, say, 85° C. In particular, the Board believes that DOE should use performance assessment to evaluate a low- temperature, ventilated design concept. If necessary, performance assessment models should be modified to portray accurately the effects of temperature changes on performance. Associated levels of uncertainty in repository performance should be developed for both high- and low-temperature design concepts. The Board realizes that DOE also may want to examine other design-related considerations, including licensability, operations and logistics, flexibility, cost, etc. The more technically defensible and quantitative the evaluation and comparison, the more useful it will be for policy-makers.

July 2, 2001, letter to Jane Summerson [comments on the supplement to the draft environmental impact statement]

The Board believes that the technical basis for projecting the long-term performance of the base-case (high-temperature) repository design has weaknesses. They include the apparently large uncertainties in projections of repository performance caused by the relatively high temperatures produced by the base-case design. The Board has urged the DOE to evaluate a low-temperature design so that its performance (and uncertainties in performance) can be compared with that of the high-temperature design. The DOE decided to address this area of Board concern by taking a single general repository design (referred to as the "Science and Engineering Report [S&ER] flexible design") and comparing its performance and associated uncertainties when it is operated at a high temperature and at a representative lower temperature. This choice was influenced, in part, by the fact that the same process models and performance assessments could be used to evaluate both the higher- and the lower-temperature design concepts. Information in the *Supplemental Science and Performance Assessment* report should provide some indication of the validity of this analytical approach. The final EIS should justify use of the S&ER design operated in a low-temperature mode as a surrogate for a true low-temperature design for purposes of projecting environmental effects, especially long-term releases of radionuclides to the environment.

The supplement to the draft EIS shows, in Table 3-14, that the peak annual dose and the time of the peak are exactly the same for the higher- and lower-temperature operating modes. Because corrosion rates, coupled processes, and the size of the repository footprint are likely to be temperature-dependent, the Board is concerned that this result may reflect model limitations. In its September 2000 letter to the DOE, the Board identified a number of limitations in the

DOE's performance assessment models that could hinder an accurate prediction of the effects of temperature on repository performance. The Board recommends that the DOE revise its performance assessment models to capture the effects of temperature more accurately, allowing an improved assessment of the merits of higher-temperature versus lower-temperature repository designs.

July 17, 2001, letter to Lake Barrett [feedback from May 2001 Board meeting]

In its response to a written question from Representative Joe Barton last August, the Board concluded that the technical basis for projecting the long-term performance of the Project's base-case (high-temperature) repository design has "critical weaknesses." These weaknesses include the apparently large uncertainties associated with projections of repository performance that are due to the relatively high temperatures produced by the base-case design. The Board therefore urged the Project to evaluate a low-temperature design and to compare its performance with the high-temperature design as a means of gaining further insights into system performance and reducing key uncertainties.

The Project decided to address this area of Board concern by taking a single general repository design and comparing its performance and associated uncertainties when it is operated in a high-temperature mode and in a selected low-temperature mode. This choice was influenced, in part, by the fact that the same process models and PA's could be used to evaluate both modes.

It is premature to determine whether the Project's approach, presented at the May meeting and elaborated in a letter to the Board dated May 30, 2001, will address adequately the questions the Board raised. We look forward to examining closely the content of the *SSPA* to ascertain whether the Project actually has gained the needed further insight. In particular, the Board is looking for clarity of objectives, transparency in design evaluation and comparison (including the Project's choice of designs), adequacy of representations and analysis between natural and engineered systems, and technical defensibility of the underlying models included in PA.

As you know, the Board will hold a business meeting in late November to begin preparing its comments on the Department of Energy's (DOE) technical bases for a decision on whether to recommend the Yucca Mountain site for repository development. However, the Board's evaluation of the status of the DOE's program, including progress on the Board's four priority areas, will be made more difficult because of gaps in data and analyses. A few key examples of such gaps follow:

> *Incomplete comparison of high- and low-temperature repository designs.* The Board has stated several times that it believes there are significant problems associated with the technical basis for the DOE's base-case repository design, which is a high-temperature design. Because it appears that a lower-temperature design could reduce the significance of some of the uncertainties related to coupled processes and corrosion of the waste packages, the Board recommended that the DOE undertake a comparison of higher- and lower-temperature designs. The DOE's May 30, 2001, letter to the Board indicated that an integrated evaluation and comparison of designs would be completed before a decision

on site recommendation is made. This comparison does not appear to have been completed.

Although the *PSSE [Preliminary Site Suitability Evaluation]* suggests that the DOE believes that its repository design can be operated over a range of temperatures, the DOE's plans, if any, to increase its understanding of low-temperature operations are unclear. For example, in general, the analyses in the *PSSE* show little difference in performance and levels of uncertainty between high- and low-temperature operations. This could mean that repository performance and levels of uncertainty are not affected by the repository's thermal regime or that the DOE's performance assessment models are not sufficiently sensitive to show differences between high- and low-temperature regimes.

Letter Report to the U.S. Congress and the Secretary of Energy. January 24, 2002.

This letter, intended as technical input for use by policymakers deciding on the suitability of Yucca Mountain for a repository (i.e., the site recommendation), contains the results of the Board's evaluation of DOE's technical work and the Board's overall conclusions that:

(1) 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;
(2) the Board has limited confidence in current performance estimates generated by the DOE's performance assessment model;
(3) no individual technical or scientific factor has been identified that would automatically eliminate Yucca Mountain from consideration as the site of a permanent repository.

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.

Strengths [for the in-drift physical and chemical environment] 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.

Weaknesses [with regard to waste package degradation] include lack of data on corrosion at high temperature under repository relevant environmental conditions…

Weaknesses [regarding water diversion by the engineered barrier system] 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.

[D]ata on aqueous corrosion for Alloy 22 above about 120º 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.

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.

March 11, 2002, letter to Lake Barrett [feedback from January 2002 Board meeting]

The DOE's current base-case repository design would produce temperatures on the waste package of 120 ºC or higher for 500 to 1,000 years and peak temperatures as high as approximately 160 ºC. The Board questions the DOE's conclusion that there is no significant long-term difference in repository performance predictions that is attributable to temperature. That conclusion appears to be inconsistent with statements by DOE scientists at the meeting indicating that uncertainties in hydrologic processes increase at higher repository temperatures. Furthermore, experimental work and analyses clearly indicate that potentially corrosive aqueous environments are possible in a repository at Yucca Mountain at temperatures up to approximately 160 ºC. Yet, the DOE has essentially no corrosion data for Alloy 22 above 120 ºC under repository-relevant conditions. Therefore, assessing the likelihood that localized corrosion could penetrate waste packages (causing them to fail) during the first few thousand years after repository closure is not possible currently. These uncertainties weaken the technical basis of the DOE's performance predictions.

May 22, 2002, letter to Hon Joe Barton in response to Hon Ed Markey's questions contained in Hon Joe Barton's letter to the Board of April 22, 2002

The severity of corrosion tends to increase with increasing temperatures. In fact, some forms of corrosion are not even observed unless the temperature exceeds a certain threshold value. This applies to essentially all alloys and metals used as construction materials, including Alloy 22, the material that the DOE has chosen to provide corrosion resistance for its waste package. In addition, and perhaps more important, predicting the chemistry (composition and strength) of salt solutions contacting the waste packages becomes more difficult and more uncertain with increasing temperature. The type and severity of corrosion depend on the makeup of those solutions.

[D]ata on the chemistry of salt solutions that may contact the waste package as well as data on corrosion of Alloy 22 exposed to such waste package environments are both essentially nonexistent for temperatures above 120° C. These key data needed to assess the likelihood that corrosion could penetrate waste packages during the 10,000-year regulatory period. This absence of information weakens the technical basis of the DOE's performance estimates for its high-temperature, base-case repository design. Uncertainty about waste package performance decreases, however, with lower repository temperatures because more corrosion data and more data on the chemistry of salt solutions that may contact waste package surfaces are available. Uncertainty also is reduced with low temperatures because corrosion severity generally decreases as temperatures decrease. The Board believes, therefore, that 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.

At this point, on the basis of the information developed by the DOE 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. Underlying this belief are the following suppositions: that temperatures and chemical conditions on the waste-package surface will be no more severe or uncertain than those in the DOE's preliminary analysis of the low-temperature operating mode; that supporting research will be continued to fill in data gaps and to rule out unexpected modes of failure; that research, development, and demonstration of waste-package welding, fabrication, and inspection are completed successfully; and that no major "surprises" are found.

June 20, 2002, letter to Margaret Chu [feedback from May 2002 Board meeting]

One objective of repository design is to provide tunnel environments that will slow waste package corrosion and minimize its associated uncertainties. As you know, the Board believes that high temperatures increase uncertainties and decrease confidence in the predictions of performance of waste package materials. Therefore, the Board is encouraged that the DOE is committed to preserving the option of a low-temperature repository. However, the technical basis for the DOE's selection of a high-temperature repository design for a potential license application remains unclear to the Board, particularly in view of the uncertainties associated with a high-temperature design and the lack of data on high-temperature corrosion. Furthermore, the DOE's current high-temperature repository design differs from the one assumed in the documentation for the site recommendation in key areas, such as waste package spacing. Finally, design flexibility deserves further analysis in light of recent ventilation calculations and the current uncertainties about the thermal conductivity of the rocks in the repository horizon. Seriously considering designs other than the DOE's current high-temperature base-case design may be of considerable value to the program if it proceeds into the licensing phase.

November 22, 2002, letter to Margaret Chu [feedback from September 2002 Board meeting]

The Board has reviewed your letter of September 6, 2002, and the DOE presentations on repository design at the Board's May and September meetings. Still unclear to the Board are what decisions the DOE has made about repository design. However, in your September 6, letter and the DOE presentations, the DOE appears to have decided to seek a license for constructing a repository based on a design "*… that results in thermal conditions at the higher end of the expected range, provides a better balance of postclosure thermal conditions and preclosure advantages for construction and operations, flexibility and cost.*" We request that the DOE provide the Board with the criteria, analyses, and weighting factors that constitute the technical basis for the apparent selection of the repository design as stated in your September 6, letter.

According to the DOE presentation made at the September Board meeting, the DOE's design decision seems to be supported by the following two conclusions: (1) projected performance for the high-temperature design is comparable to a low-temperature design and, in any case, is well below the regulatory limit; and (2) *overall* uncertainty in the projected performance of the two designs is roughly equivalent. In response to the DOE's decision, the Board has several comments on the technical basis for these assertions.

The DOE's presentation on corrosion testing may call into question the first conclusion. The increase in corrosion potential due to the presence of nitrate leads to less of a margin at temperatures above 140°C. Moreover, in back-up material from the presentation, the short-term weight-loss measurements based on linear polarization, when extrapolated to higher temperatures, show a significant increase in the rate of corrosion and indicate a definite thermal dependency that is not reflected in current models of performance assessment. The Board encourages continued corrosion testing and analysis supporting *basic understanding* of waste package corrosion and the in-drift environment.

Regarding the second conclusion, the DOE asserted at the meeting that performance assessment shows that the ranges of dose uncertainty for high- and low-temperature repository designs are similar. The Board notes that performance assessment is not capable of showing uncertainty unless the models appropriately incorporate uncertainty. Some parts of some key performance assessment models for the evolution of waste package environments and for corrosion at high temperatures are not based on data but on a number of *assumptions.* For example, TSPA assumes that there will be no liquid water above 120°C and no significant separation of chloride ions from beneficial anions and that low-temperature corrosion models are valid at high temperatures. To use these assumptions about high-temperature uncertainties as input into TSPA models and then say that performance assessment reveals that uncertainties are equivalent for high- and low-temperature operations constitute, in the Board's view, circular and therefore faulty reasoning.

The Board has noted for quite some time that the DOE's estimates of the total uncertainty in projected repository performance presume that the underlying conceptual models used to analyze both the low-temperature design and the high-temperature design are appropriate. For example, the models should capture relevant thermal sensitivities in a technically defensible manner. Many experiments, such as the drift-scale thermal test and additional high-temperature material investigations, have not been completed. Thus, the DOE's second conclusion may be premature.