U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

REPORT TO THE U.S. CONGRESS AND THE SECRETARY OF ENERGY

January to December 1993

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
1100 Wilson Boulevard, Suite 910
Arlington, VA 22209

May 1994

The Honorable Thomas S. Foley
Speaker of the House
United States House of Representatives
Washington, D.C. 20515-6501

The Honorable Robert C. Byrd
President Pro Tempore
United States Senate
Washington, D.C. 20510-1902

The Honorable Hazel R. O'Leary
Secretary
U.S. Department of Energy
Washington, D.C. 20585

Dear Speaker Foley, Senator Byrd, and Secretary O'Leary:

The Nuclear Waste Technical Review Board (the Board) herewith submits its tenth report, *Nuclear Waste Technical Review Board, Report to the U.S. Congress and the Secretary of Energy, January to December 1993*. Congress created the Board to evaluate the technical and scientific validity of the Department of Energy's (DOE) program to manage the permanent disposal of the nation's civilian spent fuel and high-level radioactive waste. Specifically, the Board is charged with evaluating the DOE's site-characterization activities at Yucca Mountain, Nevada, as well as activities relating to the design of the repository and to the packaging and transport of spent fuel and high-level radioactive waste. The Board is required by the Nuclear Waste Policy Amendments Act of 1987, Public Law 100-203, to report its findings, conclusions, and recommendations at least twice each year.

This report reviews conclusions and recommendations that have resulted from the Board's activities primarily during 1993. In a few cases, activities that took place during 1992 and 1994 also are discussed. Since its last report on the exploratory studies facility, in October 1993, the Board has continued its interactions with the DOE, the state of Nevada, and with others involved in or concerned about the civilian radioactive waste management program. In this report, the Board makes a number of technical recommendations that it believes will aid the DOE in its endeavors to design and implement a safe and efficient radioactive waste disposal system. We also discuss briefly some of the insights the Board gained during its interactions in June 1993 with experts from high-level waste management programs in Belgium, France, and the United Kingdom.

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We thank you for this opportunity to serve the nation and Congress. As our work progresses, we hope to continue to assist you in furthering the goal of safe and cost-effective management of civilian spent fuel and defense high-level waste.

Sincerely,

John E. Cantlon, Chairman	Clarence R. Allen
Garry D. Brewer	Edward J. Cording
Patrick Domenico	Donald Langmuir
John J. McKetta, Jr.	D. Warner North
Dennis L. Price	Ellis D. Verink, Jr.

NUCLEAR WASTE TECHNICAL REVIEW BOARD

Members of the Board

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Executive Summary

The Nuclear Waste Technical Review Board addresses issues and makes recommendations in this report that have evolved as a result of activities undertaken by Board members *primarily* between January 1, 1993, and December 31, 1993. In a few instances, relevant issues are discussed that were addressed during Board meetings in 1992 or 1994. Those instances are clearly designated.

Summary of Board Activities this Reporting Period

In addition to six Board-sponsored meetings held in locations around the country, members of the Board had the opportunity to interact on a number of occasions with U.S. congressional committees. On July 1, 1993, Dr. John Cantlon, Board Chairman, testified before a joint hearing of the House Subcommittee on Energy and Power, Committee on Energy and Commerce, and the Subcommittee on Energy and Mineral Resources, Committee on Natural Resources. Board members Clarence Allen and Dennis Price also appeared on behalf of the Board to respond to questions from subcommittee members. The hearing was initiated by the chairmen of the two subcommittees, Representative Philip Sharp and Representative Richard Lehman, to address concerns raised in the Board's March 1993 *Special Report to the Congress and the Secretary of Energy.*

On November 8, 1993, members of the senior professional staff represented the Board at a field hearing of the House Committee on Energy, Subcommittee on Science, Space, and Technology in Newport News, Virginia. The subcommittee asked the Board to comment on the potential of the multipurpose container concept and related research and development needs.[1]

On March 14, 1994, Chairman Cantlon and Board member D. Warner North testified before the House Subcommittee on Energy and Water Development, Committee on Appropriations. Dr. Cantlon's statement presented the Board's fiscal year 1995 budget request and outlined concerns raised in the Board's *Letter Report* to Congress and the Secretary of Energy, which was released in February 1994. (The full text of the Board's testimony on these three occasions is included in Appendix F of this report.)

Board members also had the opportunity to meet with various organizations involved or interested in high-level radioactive waste management issues, including the National Association of Regulatory Utility Commissioners (NARUC), the National Academy of Sciences, and representatives of various state utilities.

In addition to these meetings, the Board met with experts in the spent fuel and radioactive waste management programs in Belgium, France, and the United Kingdom. The Board was especially inter-

1 *In a September 30, 1993, letter to Senator Bennett Johnston, the Board had expressed its concern about language proposed for the fiscal year 1994 Energy and Water Development Appropriations bill that the Board believed could lead the DOE to make decisions in the short term about the multipurpose container concept that might preclude more desirable options later on.*

ested in the underground research that has been under way in Belgium for approximately 20 years in the medium under consideration for an underground repository. The Board was interested to find that, based on the geotechnical experience and as a result of underground in-situ testing, the Belgian repository's reference design has undergone substantial changes; the Belgian program has found that it is important to keep the program flexible so that the design can evolve to reflect new information gathered during underground research.

Finally, various Board members and staff attended several international activities this year, including the International High-Level Radioactive Waste Management Conference in Las Vegas, Nevada; Safe Waste 93, in Avignon, France; and the 1993 International Conference on Nuclear Waste Management and Environmental Remediation in Prague, Czech Republic.

OCRWM Program in Period of Flux

During the period covered by this report, several important developments took place that have implications for some of the technical issues discussed in this report. As a result of the change in administrations in January 1993, new management has been installed both at the OCRWM headquarters and at the Yucca Mountain Site Characterization Office. Under the leadership of the OCRWM's new director, Dr. Daniel A. Dreyfus, a number of modifications to the program have been initiated or proposed. An important example is the DOE's decision to aggressively pursue the development of a multipurpose container (MPC); this decision will affect all components of the waste management system.

In addition, the OCRWM is evaluating several new program strategies based on different funding levels. The OCRWM's preferred strategy, which assumes increases in funding for this fiscal year and continuing increases in future years, would bring changes in the site-characterization and licensing approach for Yucca Mountain. This new program scenario includes:

- the development and initial procurement of the MPC by 1998, which can be used for both transport and storage of spent fuel (depending on final design, these containers also may potentially be used for disposal of the spent fuel in a repository);

- the downsizing of the underground and surface-based testing programs;

- a phased-licensing approach relying on postemplacement confirmatory testing; and

- extending the period of waste retrievability from the current 50 years to 100 years.

The implications of these and other changes for the program will be evaluated by the Board as part of its ongoing technical and scientific review of the program. For the purposes of this report, however, no attempt has been made to incorporate an assessment of the effects of the potential program modifications.

Technical Recommendations based on Panel Input

The technical recommendations that follow are intended to aid the DOE in its efforts to improve the scientific work being conducted in its civilian radioactive waste management program. The recommendations are based on material that has been presented by the DOE to the Board in formal meetings or during formal interactions between DOE personnel and Board staff primarily during 1993.

Transportation and Systems

1. The Board recommends that the DOE complete the systems analysis necessary to support decisions about MPC development. This analysis should determine if the various potentials of the MPC concept can be achieved in a practicable way. It should also provide a technical basis for decisions related to MPC performance attributes and design features and for developing schedules and milestones.

2. To avoid prematurely dropping the disposal function, the Board recommends that DOE begin to address in a technically substantive way the issue of

how a *true* multipurpose container can evolve and be implemented given what is known today and the technology that is practical today, despite all of the uncertainties associated with repository design.

Engineered Barrier System

1. The DOE should continue and extend its examination of the assumptions used for its MPC conceptual designs, ensuring that the examination includes *all* of its design assumptions. The potential effects of these assumptions on waste package maximum capacity as well as on waste package performance, safety, and costs should be carefully evaluated.

2. In consultation with the NRC, the DOE should change the baseline designs for the repository and the waste package to reflect current thinking.

3. The Board encourages the DOE to examine seriously the principle of extended retrievability for a geologic repository and to avoid designs and decisions that could forestall implementation of the concept.

4. The DOE should develop plans for examining fillers. Even if specific filler materials are not selected until later, methods for using or retrofitting with fillers in the perhaps soon-to-be-deployed MPCs should be developed now.

5. The DOE should continue to examine the role of zircaloy cladding as a barrier and should recommence and accelerate research on metal joining and nondestructive evaluation of metals and welds.

Structural Geology and Geoengineering

1. The Board continues to encourage the DOE to operate the tunnel boring machine as continuously as possible while excavating the portal-to-portal main loop. Machine operations should be delayed only to recover those data that otherwise would be irretrievably lost.

2. Regardless of the funding level, the program should be restructured to ensure that critical site-characterization activities be funded adequately and dependably.

3. The Board recommends that the DOE develop a contingency plan and schedule for the site-characterization project that reflects a relatively level budget. *The plan should favor activities critical to determining the suitability of the site, incorporate a rigorous prioritization of activities, and encourage a greater sensitivity to cost control by the DOE and its contractors.* In the event that the budget is increased, a well-defined plan will provide a good basis for expanding site-characterization efforts.

4. The Board recommends that the DOE consider hiring commercial drilling companies to provide the needed drilling capacity in lieu of purchasing additional LM-300 drill rigs.

Risk and Performance Analysis

The DOE should prepare and implement a plan to increase the quality and effectiveness in the use of expert judgment in the high-level waste program. This plan should include:

- establishing guidelines for the use of expert judgment in both programmatic studies and performance assessments;
- increased involvement of management in planning and monitoring the use of expert judgment;
- increased use of *outside* (of the DOE and its contractors) expert judgment; and
- development of an experience base that includes the use of expert judgment in both internal studies and those involving interaction with external groups such as the NRC.

The Board would like to have this plan presented for discussion at a 1994 Board meeting.

Hydrogeology and Geochemistry

1. The DOE should develop a more coherent plan for using total system performance assessment (TSPA) studies and related sensitivity analyses to (a) focus future source term model development and (b) guide data collection both in terms of prioritizing research and establishing when sufficient information has been obtained.

2. The DOE should improve its capability to model radionuclide sorption and to model fully coupled reactive transport. The DOE needs to carefully compare the merits of further development of EQ3/6 versus adoption and further development of simpler codes.

3. The Board recommends that, as a high priority, the DOE begin to collect and document data on mass-transport of radionuclides in near-field materials under partially saturated conditions. These data should then be incorporated into the DOE's source term model.

Environment and Public Health

1. The DOE should develop studies of the dynamics of the Yucca Mountain ecosystem. Studies of water, energy, or nutrient transfers within the ecosystem should be considered, as should studies of the effects of repository heat on ecosystem processes. The goal of the studies should be to identify those components of the ecosystem that are most important for ecosystem health and the components that are likely to be the most sensitive to site-characterization activities, to repository construction and operation activities, and to the long-term presence of a repository at the site. The DOE should develop one or more models of the Yucca Mountain ecosystem based on water, energy, or nutrient transfers. This synthesis should come from integrating the environmental data with the geologic and hydrologic USGS data and models. The model(s) should be used to periodically (e.g., yearly) reevaluate and prioritize future environmental studies.

2. The DOE should pursue its plans to revise its ecological study plot design. The revised design should be reviewed by a statistician experienced in this type of monitoring before the new control plots are established. The DOE should consider conducting experiments in which disturbances would be deliberately applied to study plots to provide a basis for understanding the effects of site characterization on the Yucca Mountain environment.

3. The DOE should accelerate its development of a strategy for acquiring the technical information needed to forecast the environmental effects of a Yucca Mountain repository. For purposes of evaluating the possible linkages between environmental effects and repository performance, the strategy should include an assessment of a "worst-case" scenario involving the elimination of all vegetation on Yucca Mountain. The scoping process for development of an environmental impact statement should be started as soon as practical to identify major programmatic decisions for which a formal evaluation of environmental impacts is required.

Resolving Difficult Issues — Future Climates

The successful disposal of spent fuel and high-level radioactive waste in a geologic repository demands that those individuals and organizations responsible for siting and construction of the repository address a number of difficult scientific issues. These are typically characterized by great complexity, uncertain processes, and time frames orders of magnitude greater than those previously considered in human endeavors. Resolving these difficult issues requires gathering the appropriate data, increasing scientific understanding, and effective program management. It also requires clear insight into the role the difficult issues play in the overall goal of the program, that is, the safe and efficient disposal of radioactive waste. Such insight is essential in deciding how much effort needs to be expended on a particular issue. Difficult issues often necessitate difficult decisions on when "enough is enough." With this in mind the Board convened a meeting in Reno, Nevada, on April 21-22, 1993, on resolving difficult issues, using infiltration and future climates as the issue. In this report the Board concentrates on future climates.

The Board concludes that the DOE needs to develop a coherent strategy to address climate-related issues at Yucca Mountain. The guiding principle of this strategy should be to frame the prediction of future climates (taking into account existing techniques and potential capabilities) in the context of program needs and not theoretical science. This strategy should include: an understanding of how climate change can cause the repository system to fail; analysis of the relevant geologic past as the key to determining future climate effects; the use of climate models in a supportive role; and formation of a panel of experts on climate. Finally, the DOE at some time will have to decide when it has reached the point of diminishing returns with respect to its climate-related studies for the Yucca Mountain site. The primary element in this decision should not be the ability to predict future climate at Yucca Mountain, but rather the ability to determine, with sufficient confidence, whether future climate states will or will not cause the repository to fail.

Recommendations

The Board makes the following recommendations with regard to this issue.

1. The DOE needs to develop a strategy for addressing climate-related issues that is based upon their significance to repository performance rather than the ability to predict future climate alone.

2. Future climate states should be estimated primarily through the use of paleoclimatic and paleohydrologic data. Numerical modeling can play a supplementary, but important, role in overcoming the limitations of the paleoclimate data and estimating the likelihood of adverse climate states.

3. An external expert panel made up of atmospheric scientists, paleoclimate data analysts, hydrologists and specialists from other relevant disciplines should be formed to help guide the DOE in the integrated use of data and models. The chief scientist, when appointed, should play a key role in integrating the studies and coordinating the expert panel.

4. The range of future climate states at Yucca Mountain should be an acknowledged input to repository design.

One important question remains: Is this approach valid for other difficult issues? It is appropriate to ask whether the approach recommended by the Board in this report is applicable to other issues, and the answer is yes — with some important caveats. The call for a coherent strategy based on program needs is clearly applicable to the range of problems faced at Yucca Mountain. So is the need to understand how the process or phenomenon under consideration can cause the repository system to fail. This, for example, was the approach recommended by the Board in its *Second Report* with respect to earthquake hazard at Yucca Mountain. Similarly, the criteria for determining when enough is enough is generally applicable. However, the interaction between, and priorities assigned to, data and numerical models is clearly problem specific. Much depends on the availability, quality, and usefulness of data, and on the level of confidence that can be placed on numerical models. The need for external expert panels is also problem specific. Although the Board has generally called for the inclusion of more external expert advise in the program (see the section in this report on risk and performance analysis), the need to specifically convene a panel is not applicable to all problems. In many cases, a less formal arrangement exposing the views of project scientists and engineers to outside comments may be all that is needed.

Introduction

In the United States today, commercial nuclear power facilities produce almost 21 percent of the nation's electric power. One by-product of nuclear energy production, radioactive spent nuclear fuel, is accumulating at the nation's nuclear power plants. Because of its radioactivity, it will require isolation from the public and the accessible environment for thousands of years.

In 1982, Congress assigned the U.S. Department of Energy (DOE) the responsibility of designing and implementing a system to manage the disposal of this spent fuel. Also included for disposal is the country's high-level radioactive waste from defense-related activities. Current plans call for the construction of a underground geologic repository that will isolate the waste for at least 10,000 years.

But creating a system to manage the disposal of spent fuel and high-level radioactive waste involves more than constructing a deep, geologic repository. It involves designing, developing, and implementing a complex system to package, collect, store (for either short or long periods of time), transport, and, finally, dispose of the radioactive waste from public utilities and defense facilities located across the country. All of the components of the system must *work together* safely and efficiently. One major challenge involves demonstrating to the satisfaction of the regulators and the scientific and lay communities that workers in the system — and the public at large — can be protected and that the highly radioactive material will remain safely isolated for the long periods of time that regulating agencies require.

In 1987, Congress chose a site at Yucca Mountain, Nevada, to be evaluated for its suitability as a possible location for a repository. In that same legislation Congress created the Nuclear Waste Technical Review Board as an independent establishment within the executive branch. Congress charged the Board with evaluating the scientific and technical aspects of the DOE's program; the Board submits its findings, conclusions, and recommendations to Congress and the Secretary of Energy. The Board's first report was released in March 1990. Reports are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 or from the Board's Arlington, Virginia, offices.

Chapter 1
Background

The Nuclear Waste Technical Review Board addresses issues and makes recommendations in this report that have evolved as a result of activities undertaken by Board members *primarily* between January 1, 1993, and December 31, 1993. In a few instances, relevant issues are discussed that were addressed during Board meetings in 1992 or 1994. Those instances are clearly designated.

Chapter 1 summarizes the Board's activities and reviews several areas that are not discussed in other chapters; for example, Board interactions with the Congress related to the Department of Energy's (DOE) program, meetings with other organizations involved or interested in radioactive waste management issues, and the Board's interactions with experts from programs in other countries. Chapter 2 contains a discussion of specific technical issues and is organized by Board panel topics. Chapter 3 discusses a meeting the Board held on resolving difficult issues, specifically, future climates.

Summary of Board Activities this Reporting Period

From January 1, 1993, through December 31, 1993, the Board and its panels sponsored six meetings. A chronological list of the Board's activities (beginning January 1993 and including those scheduled for the future) can be found in Appendix C. A list of the people who made presentations at Board- and panel-sponsored meetings has been included in Appendix D.

In addition to these meetings, the Board met with experts in the spent fuel and radioactive waste management programs in the United Kingdom, Belgium, and France. Insights from these meetings are discussed below; background material on the three programs has been included in Appendix H. In addition to these meetings, various Board members and staff attended the International High-Level Radioactive Waste Management Conference in Las Vegas, Nevada; Safe Waste 93, in Avignon, France; and the 1993 International Conference on Nuclear Waste Management and Environmental Remediation in Prague, Czech Republic.

Finally, during the past year Board members and staff have met with various organizations involved or interested in high-level radioactive waste management issues, including the National Association of Regulatory Utility Commissioners (NARUC), the National Academy of Sciences (NAS), and representatives of various state utilities.

Other Areas of Interest

In addition to its regular activities, the Board Chairman had the opportunity on several occasions to interact with Congress. The Board also was asked to respond to questions posed by the National Academy of Sciences relating to the NAS review of the technical bases for public health and safety standards applicable to a repository at Yucca Mountain. These areas of interest and the Board's recent publications are reviewed briefly below.

Board Interactions with Congress

On July 1, 1993, Dr. John Cantlon, Board Chairman, testified before a joint hearing of the House Subcommittee on Energy and Power, Committee on Energy and Commerce, and the Subcommittee on Energy and Mineral Resources, Committee on Natural Resources. Board members Clarence Allen and Dennis Price also appeared on behalf of the Board to respond to questions from subcommittee members. The hearing was initiated by the chairmen of the two subcommittees, Representative Philip Sharp and Representative Richard Lehman, to address concerns raised in the Board's March 1993 *Special Report to the Congress and the Secretary of Energy*. Issues identified in a GAO report on the civilian radioactive waste management program also were discussed at the hearing.

Dr. Sherwood Chu, senior professional staff, represented the Board at a field hearing of the House Committee on Energy, Subcommittee on Science, Space, and Technology on November 8, 1993, in Newport News, Virginia. Dr. Chu was accompanied by Dr. Carl Di Bella, another member of the Board's senior professional staff. The subcommittee asked the Board to comment on the potential of the multipurpose container concept and related research and development needs. In a September 30, 1993, letter to Senator Bennett Johnston, the Board had expressed its concern about language proposed for the fiscal year 1994 Energy and Water Development Appropriations bill that the Board believed could lead the DOE to make decisions in the short term about the multipurpose container concept that might preclude more desirable options later on. This issue is discussed in more detail in Chapter 2 in the section on Transportation and Systems.

On March 14, 1994, Dr. Cantlon, and Dr. D. Warner North, testified before the House Subcommittee on Energy and Water Development, Committee on Appropriations. Dr. Cantlon's statement presented the Board's fiscal year 1995 budget request and outlined concerns raised in the Board's *Letter Report* to Congress and the Secretary of Energy, which was released in February 1994. Dr. Daniel Dreyfus, director of the OCRWM, and Nuclear Waste Negotiator Richard Stallings also testified at the subcommittee hearing. The full text of the Board's testimony on these three occasions is included in Appendix F.

Radiation Protection Standards

The Energy Policy Act of 1992 called for a review, by the National Academy of Sciences, of technical bases for public health and safety standards applicable to a repository at Yucca Mountain. On May 27-29, 1993, a committee of the National Academy of Sciences initiated its review. During its first meeting, members of the committee asked for a more detailed explanation of a Board recommendation in its *Third Report* that regulations and standards should be "risk based." The Board responded by describing the following two meanings it intends when using the term "risk based."

Include probabilities of exposure

Regulations should limit the risks of low-probability, high-consequence events as well as more likely events with more moderate effects. Thus, the Board uses the term "risk based" to include consideration of both the radiation doses humans might receive and the probabilities that those doses will actually occur. Standards that merely impose dose limits cannot properly address the acceptability of low-probability, high-dose events.

The Board sees no conflict between its recommendation for risk-based standards and the suggestion in the 1992 Energy Policy Act for a "standard based on doses to individual members of the public." Consistent with the Act, a risk-based standard could be based on doses to members of the public, with different dose levels allowed for different probabilities of exposure.

Focus on threats to human health

The Board questions whether standards should be derived solely (or even primarily) from consideration of the technological capabilities of waste disposal. The technology for disposing of high-level wastes is still evolving. The lack of a well-developed and proven disposal concept leads to the prospect that technology-based standards, developed today, could prove to be either too stringent or not stringent enough when long-term repository performance is better understood. As an example, recent recognition of the potential for gaseous release of carbon-14 from an unsaturated zone repository has raised the possibility that previous standards might have been overly stringent for protecting human health from releases of that radionuclide, which is common in natural environments. Because the technology of deep geologic disposal is not yet fully developed, it seems unwise to base standards solely on the projected specific radionuclide isolation capabilities of repositories. Instead, it might be more appropriate to derive standards primarily from considerations of the need to protect public health. In fact, this seems to be the intent of the 1992 Energy Policy Act when it refers to a “health-based standard.”

Board Publications

The Board issued two reports during 1993. The *NWTRB Special Report to Congress and the Secretary of Energy* was released in March 1993, and *Underground Exploration and Testing at Yucca Mountain* was published in October 1993. The former outlined three broad-based concerns that the DOE should address to increase the integrity of the scientific and technical programs and to improve overall program effectiveness. The latter reviewed the status of the DOE’s underground exploration and testing program. In addition to a number of detailed technical recommendations, the Board made three general recommendations that it believes can be implemented without slowing the momentum of important site-characterization activities now under way at Yucca Mountain. The DOE’s responses to these reports and to the Board’s *Sixth Report* (December 1992) have been included in Appendix G.

Finally, in February 1994, the Board sent a letter report to Congress and the Secretary of Energy, in which it reiterated the recommendations it made in its *Special Report*.

These and other Board reports, are available from the U.S. Government Printing Office or the Board’s Arlington, Virginia, office. (See Appendix E for a brief summary of available Board reports.)

Observations from the Board’s trip to Belgium, France, and the United Kingdom.

In 1993, the Nuclear Waste Technical Review Board continued to learn about the spent fuel disposal programs of other countries. A Board delegation visited Belgium, France, and the United Kingdom to meet with representatives of those countries respective high-level waste programs. The Board made this trip for two reasons: (1) to learn more about programs where *reprocessing* is a central part of the waste management system and (2) to look at the underground research going on there and determine if there are aspects of these programs from which the U.S. program could benefit.

Those working in the high-level waste programs in Belgium, France, and the United Kingdom face the challenges and opportunities presented by their commitment to reprocessing spent fuel. In France and the United Kingdom, Board members visited and met with representatives of the reprocessing facilities at La Hague and Sellafield, as well as with the governmental authorities involved in directing, regulating, and reviewing those high-level waste programs. In Belgium, the Board visited HADES, the underground research laboratory at Mol/Dessel, and met with government representatives responsible for directing that country’s waste program.

Board members are grateful to experts in all three countries for the time they took from their schedules to meet with Board members and to explain their roles and responsibilities in their respective waste management programs. The Board greatly appreciated the information, and, although a number of important issues were raised and discussed, the Board has chosen to address a few select issues at this time.

Different Waste Classification Systems

Although differences exist between the waste classification systems found in the United States and the systems used in Canada, Finland, Germany, Sweden, and Switzerland, these differences played a small role during Board visits in the past because emphasis during those visits was limited for the most part to issues related to storage and disposal plans for spent nuclear fuel.[1] In contrast, however, Belgium, France, and the United Kingdom have waste disposal systems that are based on categories of waste that result primarily from the reprocessing of spent fuel. All three countries have defined slightly different waste categories, depending on their particular waste management and disposal options. For purposes of comparison, however, the European Economic Community (EEC) has prepared some *general* descriptions of the waste categories and generated uniform data on the waste generated by member states.[2] The EEC's waste categories include: low level waste, medium or intermediate level waste, alpha waste, high-level waste, and spent nuclear fuel.[3]

The United States has a somewhat more complicated waste classification system. It distinguishes low-level wastes, transuranic wastes, greater-than-class-"C" wastes, high-level wastes, and spent nuclear fuel. The U.S. Nuclear Regulatory Commission, the U.S. Environmental Protection Agency, and the U.S. Department of Energy have all been involved in defining different classes of wastes along with the requirements for their disposal. Essentially, however, in the United States the origin of the waste determines whether or not it is classified as high-level waste. If the waste is spent nuclear fuel or reprocessed waste, it is high-level waste. In a strict legal sense, all other waste is low-level waste. For practical purposes, transuranic and greater-than-class-c wastes have emerged as an "intermediate" class of waste.[4] Table 1.1 shows *generally* how the U.S. categories compare to the categories set forth by the European Economic Community (EEC).

Table 1.1 — Waste Classes: EEC and U.S.

U.S. Commercial	U.S. Defense	European Economic Community (EEC)
Low-Level Waste (Class A, B, C)	Low-Level Waste	Low-Level Waste - - - - A Waste*
Greater than Class C	Greater than Class C - - - - Transuranic	Medium- and Intermediate-Level Waste - - - - Alpha Waste - - - - B Waste*
Spent Fuel	High-Level Waste	High-Level Waste - - - - C Waste*

* The programs in France and Belgium categorize their waste according to Class A, B, C.

It is interesting to note that each of the countries visited by the Board has created a somewhat different waste classification system. Sweden, for example, is developing a waste classification system based on three categories of waste: spent fuel, operating waste, and decommissioning waste. Switzerland has defined short-lived, intermediate, and high-level wastes, but the definitions are only moderately important because all waste in Switzerland will be buried underground. In Germany, according to national law, all waste that is not low-level waste must be categorized as high-level waste.

1 *Although Germany remains committed to reprocessing, research had been undertaken at the time of the Board's visit to explore the possibilities of disposing of spent fuel directly. Also, members of the Board's Panel on the Engineered Barrier System visited Japan, but focused on specific work surrounding their EBS system.*

2 *In addition to Belgium, France, and the United Kingdom, the European Economic Community (EEC) includes Denmark, Germany, Greece, Ireland, Italy, Portugal, Spain, and the Netherlands.*

3 *These classifications relate to the concentration and type of radioactivity in the waste and hence to the intensity of emitted radiation. They are not intended to be precise definitions for each category of waste.*

4 *"Greater than class C" waste applies to commercially generated wastes but is also recognized unofficially by the DOE in its defense waste programs. It has yet to be determined exactly how and where class C wastes are to be disposed of, but general consensus seems to be that these wastes will have to be disposed of in an underground repository, similar to transuranic and high-level wastes and spent nuclear fuel.*

As a result of these differences, it is difficult to compare waste disposal plans until there is an understanding of the nature of the wastes to be disposed of, which in turn requires understanding how one country's waste classification compares to another country's. When different definitions and disposal methods are used, comparing disposal technologies and research and development (R&D) work for a particular type of waste becomes challenging. Although unlikely, developing an agreed-upon set of international definitions for all classes of nuclear waste to be used by all countries would make the task of comparing different aspects of the various nuclear waste programs easier.

Reprocessing

Reprocessing spent fuel is an integral part of waste management programs in Belgium, France, and the United Kingdom. In Belgium reprocessed waste constitutes the main source of radioactive waste. Belgium's reprocessed waste comes from past operations of the EUROCHEMIC company's reprocessing pilot plant (now called BELGOPROCESS waste) and the spent fuel that is being reprocessed by COGEMA at La Hague in France.[5]

The United Kingdom originally began reprocessing because its reactors were gas-cooled and their Magnox fuel was housed in relatively reactive magnesium cladding.[6] To ensure against leakage of the spent fuel through the cladding, Magnox fuels had to be reprocessed soon after irradiation (within 6 to 12 months) or moved into dry storage, which allows a longer storage period (possibly several years). Despite technological, public perception, and possible health and safety problems, British Nuclear Fuels Limited succeeded in developing reprocessing technology at Windscale and Sellafield. Magnox reactors were then superseded by advanced gas-cooled reactors and pressurized water reactors. British Nuclear Fuels Limited then submitted a proposal to build a thermal oxide reprocessing plant (THORP), as Britain's first major entry into the international reprocessing market. The facility, which was completed in 1992, is intended to reprocess domestic and international spent oxide fuel. The British government recently granted British Nuclear Fuels the authority to begin operations, following an environmental and economic evaluation. However, critics of THORP have argued that operation of the plant is an environmentally unsound decision and will add dangerously to the world's stockpile of plutonium, which potentially could be used in nuclear weapons production. Critics also argue that the facility, as originally conceived in the 1970s, is no longer necessary and that the costs of decommissioning THORP have not been adequately addressed in assessing its economic viability.

Great Britain's Radioactive Waste Management Advisory Committee (RWMAC), an organization created to advise the government on major issues pertaining to the management of civilian radioactive wastes, believes that THORP has the potential to be a major income earner. Business during its first ten years is potentially estimated at $4.5 billion, including contracts with 35 utilities in 10 countries worldwide. In the view of the members of the RWMAC, THORP can make an important contribution to the United Kingdom's balance of payments (RWMAC 1990). RWMAC states that a decision about the future of reprocessing depends on whether the radiological and environmental impact of reprocessing is justified by benefits to the U.K. economy. RWMAC has also urged the government to assess and take into consideration the public's attitude towards international trade in hazardous wastes (RWMAC 1990).

France, with a very strong commitment to nuclear power (57 reactors generate 76% of the country's electricity), also is a strong proponent of reprocessing. France has two major reprocessing sites with three facilities. Two facilities operated by COGEMA are at La Hague, near Cherbourg, France, where French and foreign spent fuels are reprocessed. COGEMA currently has contracts with Belgium, Ger-

5 Recently, however, the Belgian government delayed implementation of its reprocessing contracts with COGEMA for five years. The government intends to reevaluate reprocessing and consider direct disposal as an alternative.

6 In the U.S., fuel for light water reactors is housed primarily in zircaloy cladding.

many, Japan, The Netherlands, and Switzerland. The other French site is the Marcoule plant in southern France, which is dedicated to the reprocessing of gas-cooled reactor and liquid metal reactor fuels. As strong proponents of reprocessing, those involved in France's program advocate that reprocessing:

(1) reduces the volume and heat load of the disposable wastes;

(2) permits recycling of reusable uranium and plutonium and thus conserves natural uranium resources;

(3) permits sophisticated separation, conditioning, and treatment of the waste by removing long-lived radioisotopes, thereby reducing long-term risks after final disposal;

(4) provides for interim storage of treated waste forms; and

(5) recovers and uses plutonium, thus reducing the risk that intruders will enter a repository to recover plutonium for weapons proliferation.

In addition, in Law 91-1381 of December 30, 1991, the French government decided to pursue research in partitioning and transmutation as part of its continued commitment to improving its nuclear production and reprocessing capabilities.[7]

In the United States the decision was made not to reprocess civilian spent nuclear fuel after efforts to do so failed over a number of years. The history of events leading up to this decision is quite complex, but the effort to reprocess stems in part from the belief in the postwar years that uranium would become scarce due to an increased demand for its use in producing nuclear power and that commercial reprocessing and breeder reactors would be developed. Attempts to establish commercial reprocessing facilities in the 1970s, however, demonstrated that the technology in existence at the time was not necessarily established nor cost-effective. Also, as time went on, it became apparent that there were more natural uranium sources worldwide than originally believed, and that nuclear power reactors were not being ordered or built to the extent predicted (Carter 1987).

About the same time, the United States became embroiled in debate over safeguard and proliferation issues associated with reprocessing. This resulted in major U.S. policy changes by Presidents Gerald Ford and Jimmy Carter in 1976 and 1977. It was decided that support for nonproliferation should take precedence over the potential economic and energy benefits associated with reprocessing civilian spent fuel.[8] And when President Reagan attempted to reprieve reprocessing in the United States in the early 1980s, the utilities and others potentially interested from a business perspective, while expressing interest, did not regard reprocessing as a prudent short-term business investment. This reluctance, combined with numerous political, administrative, and economic obstacles encountered by the Department of Energy in its efforts to bring about the start-up of the Barnwell reprocessing facility, effectively killed prospects for commercial reprocessing in the United States (Carter 1987).[9]

Whether or not reprocessing in the nuclear industry ultimately will become advantageous from a political, economic, and / or technical perspective remains to be seen. Those advocating reprocessing make strong arguments on behalf of reprocessing, but, for a number of reasons, their arguments may not necessarily be the ones that prevail. First, the potential use of plutonium for breeder or advanced light water reactors may be very limited, given that these technologies may not undergo development and / or be used for decades to come. Second, the potential to dispose of spent nuclear fuel at considerably less

7 *Guy Baudin, CEA/DCC/Saclay, presentation to the Board, June 1993.*

8 *Those in favor of reprocessing argue that it reduces the potential for proliferation because the plutonium is recovered from the spent fuel, thereby reducing the desire to steal spent fuel for the potential weapons-grade plutonium it contains. Those opposed to reprocessing argue that potential stockpiles of recovered plutonium are equally, if not more, dangerous than stockpiles of spent fuel containing plutonium.*

9 *Reprocessing of defense spent nuclear fuel, however, did continue in the United States.*

cost than the cost of reprocessing, plus then disposing of the reprocessed waste and the waste from decommissioning the reprocessing facilities also may argue against reprocessing. Third, there was originally an incentive to send one's waste to be reprocessed because the understanding existed that the reprocessor would keep the waste (Carter 1987). In 1991, however, France passed a law that forbids the final disposal of *foreign* radioactive wastes in French soil.[10] Also, in the United Kingdom there is discussion of returning an "equivalent" amount of radioactivity to reprocessing customers because it is difficult to identify customer wastes once reprocessing has occurred (RWMAC 1990). Last, public opposition to solving the waste disposal problem associated with spent nuclear fuel and high-level waste is such that expansion of the nuclear industry in some countries has come to a virtual halt.[11] This, in turn, may argue against making substantial new long-term commitments to reprocessing until a clearer economic, political, and technological picture emerges of the industry's future.

Despite major disagreements about the advantages and disadvantages of reprocessing in Belgium, France, and the United Kingdom, the *commitment* to reprocessing has brought with it one real benefit: in those countries, a long-term system for the interim management and storage of spent fuel and high-level waste has been established, and the systems have been operating for many years. The facilities in operation at La Hague in France and at Sellafield in the United Kingdom demonstrate the technical community's ability to successfully manage, process, store, and dispose of radioactive waste. As more members of the public learn of the extent of the technical achievements at facilities such as these, there may be more willingness to develop technologies and methods for disposing of the high-level waste being stored at these facilities. Until this happens, however, these countries at least have a system in place for managing the long-term storage of radioactive wastes.

In contrast, the United States still does not have an accepted long-term interim storage and management system for its commercial spent nuclear fuel.

Conclusion

Whether or not reprocessing in the nuclear industry ultimately will become advantageous from a political, economical, and/or technical perspective remains to be seen. In Belgium, France, and the United Kingdom, however, the commitment to reprocessing has resulted in the establishment of a system for the *long-term* management and storage of high-level waste. Although it obviously is not necessary to reprocess to achieve such a system,[12] there are advantages in having such a system, particularly as efforts to site and build permanent repositories take longer than expected.

Underground Research

The underground research programs in Belgium, France, and the United Kingdom are at various stages in their development. In France, all underground research has been halted since a moratorium was enacted in 1990. Prior to that time, four candidate sites had been selected based on surveys of 30 zones covering schist, granite, salt, and clay. Underground research was in progress in, among other locations, the Fanay-Augeres Mine near Limoges (granite) and at the underground research laboratory (HADES) at Mol/Dessel in Belgium. Since the moratorium, however, all underground research has stopped. A nuclear waste negotiator has identified four potential volunteer sites where underground research laboratories could be built. ANDRA, the national agency for waste management, will conduct preliminary studies at these sites; then two will be selected at which underground research laboratories will be built and operated with the possible goal of establishing and building a permanent underground repository.

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10 Law 91-1381 of December 30, 1991, article 3.

11 This is not the case in France, however, where the industry, although growing at a slower rate (less than one reactor per year), is still growing and will be generating 75% of the country's electricity in the year 2000.

12 Sweden and Finland also have long-term storage systems in operation.

In the United Kingdom, at the time of the Board's visit, U.K. Nirex Ltd., was in the process of drilling a number of boreholes (15 in progress at present) in 500 million year old basement rocks in the Borrowdale Volcanic Group overlain by sandstone at a potential disposal site located at Sellafield. If the site were approved and developed, intermediate-level wastes would be disposed of there. The next phase of the research will consist of building an underground rock characterization facility in phases. Similar to the U.S. program, minimal underground research has been conducted in the medium under investigation prior to the current site investigation. A primary objective of U.K. Nirex Ltd's work at the site has been to assess fracturing, water flow, and salinity in the rocks surrounding the proposed repository.

Underground Research in Belgium is of Particular Interest

The Board was particularly interested in the underground research program in Belgium for a number of reasons, which are discussed briefly below.

Primary reliance on the natural barrier

In contrast to most of the other programs visited by the Board, where R&D work places primary reliance on the engineered barrier system, or the waste package, to isolate the radionuclides, in Belgium a multibarrier approach has been adopted. In the Belgian concept, the engineered structures are intended to last a few thousand years *at most*, after which time the properties of the natural geology will be relied on for containment. And as a few thousand years are insignificant compared to the time needed for retardation of radionuclides, those involved have concluded that the engineered barriers should be designed so as to provide minimum disturbance to the natural geology rather than for additional protection.[13]

Extensive research experience in the geology under consideration

For more than 20 years (since 1974), the Belgian Nuclear Research Centre (CEN / SCK) has been conducting research in the Boom Clay[14] near Mol and Dessel (in the northeastern corner of the country). Following initial work by the Belgian Geological Survey, CEN / SCK began drilling in the boom clay in 1975. From 1980 to 1984, after approximately 10 years of surface work, an underground research facility, called HADES, was built in the clay at a depth of 230 meters. In-situ confirmation experiments then became possible. A second phase, the construction of a gallery called "Test-Drift" was completed in 1987.

The HADES underground research facility has been the principal research tool in the program since that time. Many in-situ experiments and demonstration tests have been conducted there during the past 10 years. Long-term principal research has been conducted on the behavior of waste package materials, the near field, the host rock, the surrounding geologies, waste management systems design and operation, long-term performance and safety assessment, and construction. In a number of these areas, those involved have collaborated with researchers from other countries, including Spain, Japan, France, the United Kingdom, the United States, Italy, and Switzerland. Further tests are planned, such as demonstrating the combined effects that could be expected to occur in a repository. Of particular note, research has been conducted looking at the generation of gas due to corrosion of metal, which under high pressures could form fractures in the clay and compromise its desirable hydrogeological properties.

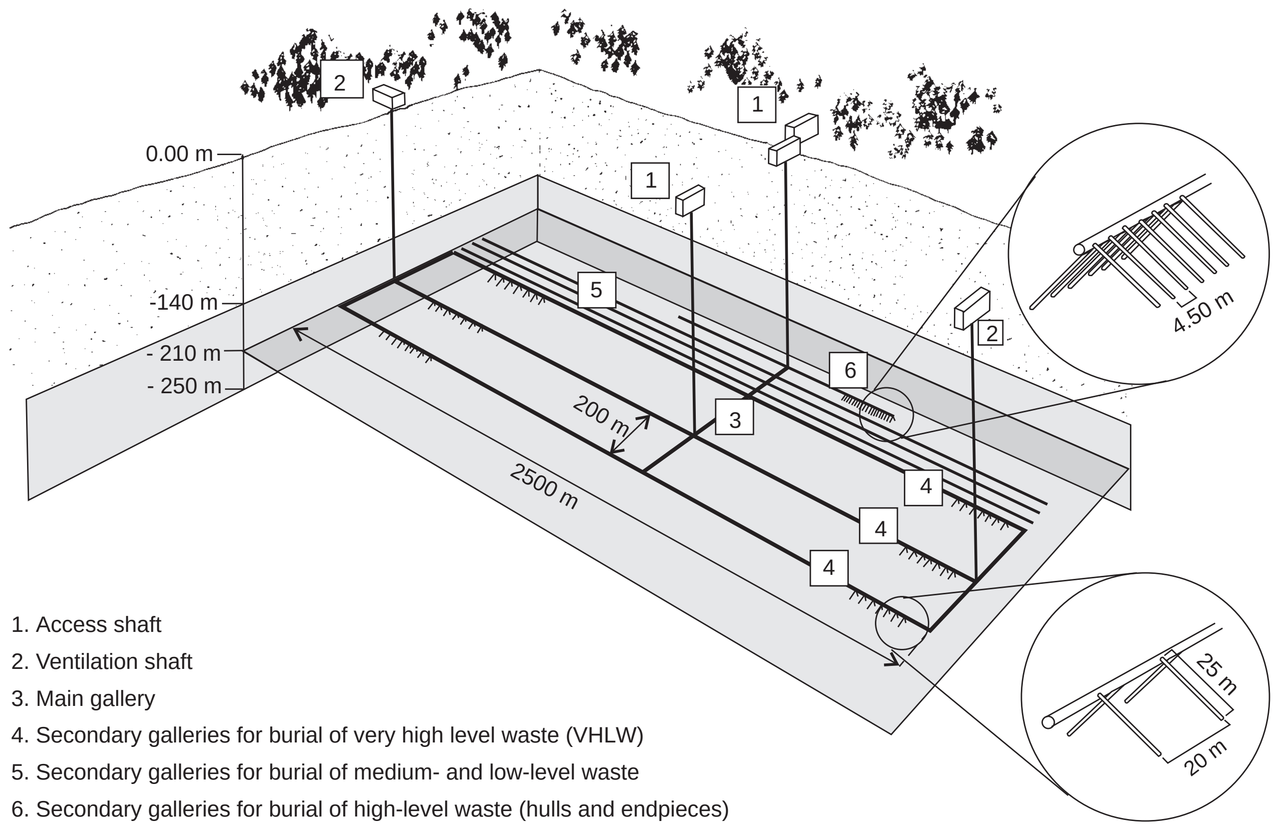
Changes in approach to repository construction

Part of the reason HADES was built was because the mechanical behavior of clay at the 230-meter depth was unknown. There was also little experience in excavating and conducting large-scale construction work in clay at depths greater than two hundred meters. Consequently, the excavation of this labora-

13 Van Miegroet, J. "Design Bases of the Belgian Repository for Vitrified Heat Producing Radioactive Wastes." (IAEA 1992)

14 This layer is 80 to 100 meters thick and covers several hundred square kilometers.

Figure 1.1 — The HADES Concept



Source: Adapted from *SAFIR — Summary Report*, ONDRAF / NIRAS, National Agency for Radioactive Waste and Fissile Materials, Brussels, Belgium, June 1989.

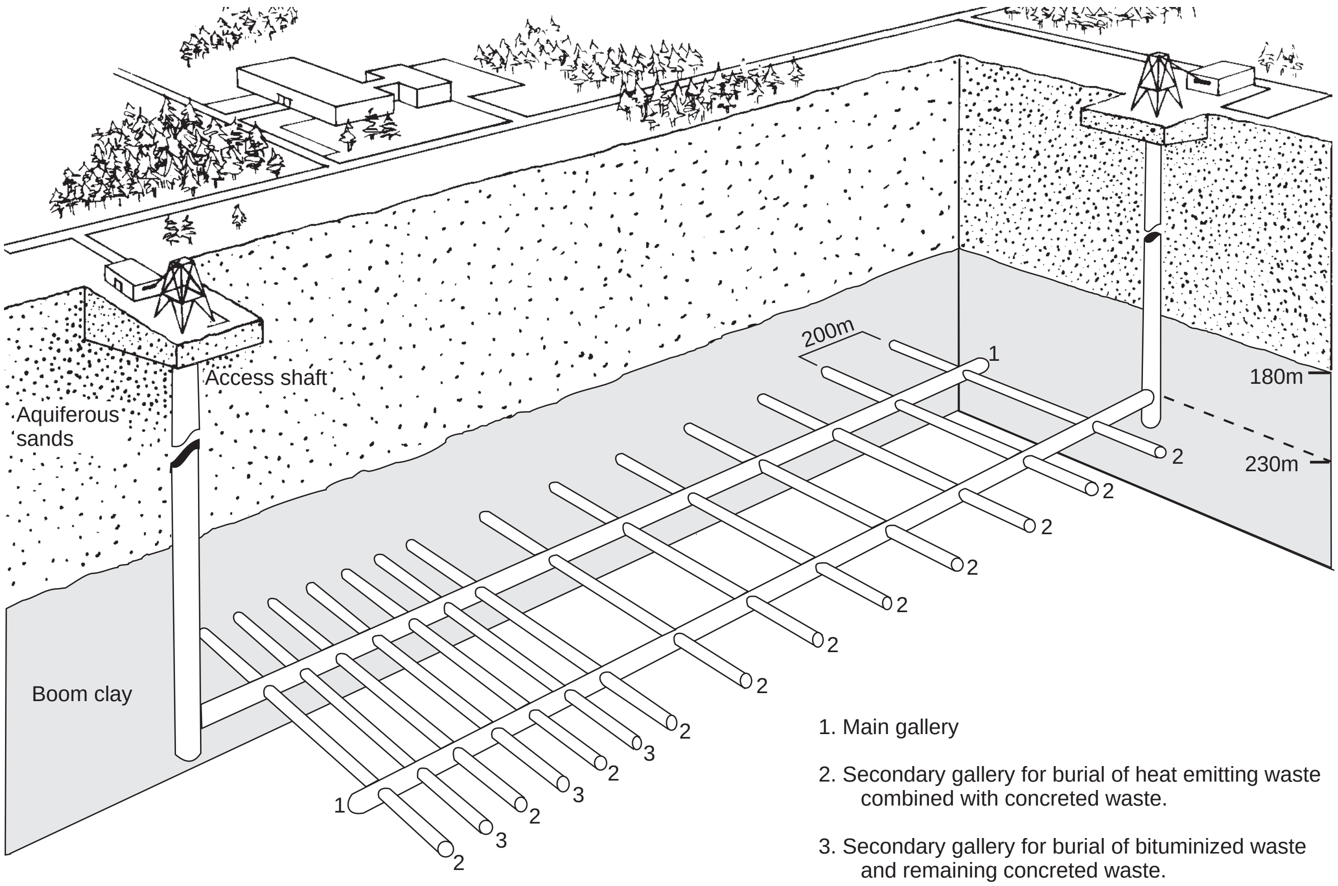
tory allowed considerable progress in geotechnical engineering. For example, through trial and error, it was learned that it is not necessary to freeze the clay prior to excavating. Also, when stresses in the lining turned out to be smaller than expected, concrete blocks were found to be acceptable (and more cost-effective) than nodular cast iron segments for lining the gallery. This geotechnical engineering approach was then further tested in the drift built in 1987.

Evolution of the program design

As the direct result of ten-plus years of in-situ experiments and the experience gained in building HADES, the Belgian reference concept underwent substantial changes. The original concept, called HADES and developed in 1978, was designed according to the maximum thermal load the host formation *was thought* to be able to tolerate. HADES consisted of a series of secondary burial galleries with a working diameter of 3.5 meters (approximately 12 ft) and lined with cast iron segments. These were connected by a main gallery that joined two access shafts (See Figure 1.1). This concept was conditioned on being able to retrieve the containers of vitrified waste for an extended period of time if necessary.

The new concept, called the “Belgian concept,” emerged as a direct result of research, mostly in the areas of thermal design and geotechnical engineering. The fundamental difference is that the new concept does not allow for easy retrieval of the primary packages during or after burial.[15] This “axial” concept consists of a series of secondary burial galleries that lead to two main galleries, which are joined to

Figure 1.2 — The Belgian Concept



Source: *SAFIR — Summary Report*, ONDRAF/NIRAS, National Agency for Radioactive Waste and Fissile Materials, Brussels, Belgium, June 1989.

the surface by two access shafts (See Figure 1.2). The advantages of this concept are stated as: simplicity of construction, reinforcement of the multibarrier effect, more homogeneous dispersion of heat in the lining and clay of the repository, limits on the radiological impact on clay, reinforcement of the stability of the engineered structures, insulation of the waste due to early backfilling of the galleries, and less disturbance of the clay layer (SAFIR 1989).

Insights from the Belgian Program for the U.S. Program

Because the U.S. program at this point has the experience of only several years of surface-based testing and minimal underground research (in G-tunnel) in the geology under consideration[16], the Board believes that the DOE could benefit from the experiences of those involved in the work undertaken by

15 *The Belgians intend to dispose of high-level waste, which no longer contains plutonium or uranium. It is the plutonium and uranium that potentially could be recycled.*

Belgium's R&D corporation (CEN / SCK) and by the governmental agency responsible for nuclear waste management (ONDRAF / NIRAS). Although much smaller than the U.S. program, the Belgian program has approximately 20 years of experience researching in the geology under consideration for a repository. (And other programs, such as Canada and Sweden, have made similar investments of time to investigate the geology under consideration.) This time investment has benefitted the Belgian repository program in two important ways.

1. As a result of their geotechnical experience and the in-situ tests performed at HADES, the Belgian repository's reference concept has undergone *substantial* changes. This suggests that plans are made with the idea that, as engineering experience is gained and technical and scientific knowledge increases, those plans are going to change. Because the Belgian program is currently only in the R&D phase and there is no pressure to meet specific deadlines to build a repository, it has the flexibility to make changes. In contrast, the U.S. program has labored under tight schedules and a prescriptive regulatory framework both of which have hindered the flexibility needed in such a first-of-a-kind program.

2. The Belgian program has made much progress since HADES was constructed and continues to believe that the HADES facility is the principal research tool in their investigations. After 10 years of research, current plans are to conduct in-situ experiments and demonstration tests aimed at describing the conditions that will exist once a repository commences operation.[17] The Belgian experience demonstrates the importance of getting underground and planning on spending some time there to learn about the potential medium.

Conclusion from the Belgian Experience.

Although the medium under investigation in Belgium is different from that under study in the United States and although its R&D program is much smaller than the U. S. program, the Belgian program may be able to offer some insights. Particular questions of interest include: (1) How much time actually will be required to conduct the studies pertinent to repository design and to understanding the geology? (2) What geotechnical experience has been gained as a result of building the underground facility? (3) What specific benefits have been derived from underground research and from joint R&D with other countries? (4) What kind of flexibility should be built into the R&D program? (5) To what extent will the reference design for a repository be expected to evolve as a result of underground R&D, including the decision to rely primarily on the natural geology to contain the radionuclides?

Answering these and other questions, such as how data derived from underground R&D can best be used in iterative performance assessment, may help the U.S. program determine the required time, structure, and scope needed to build a sound scientific and technical R&D program.

16 *Of note, however, the U.S. program does have a potential site, whereas the Belgian program could potentially be undertaking unnecessary research if the repository ultimately is not sited in Boom clay.*

17 *Bonne, A. and G. Collard. "Scientific Bases of the SCK/CEN Programme on Radioactive Waste Disposal in Argillaceous Formations. (IAEA 1992)*

Chapter 2
Panel Activities, Conclusions, and Recommendations

OCRWM Program in Period of Flux

During the period covered by this report, several important developments took place that have implications for some of the issues discussed below. As a result of the change in administrations in January 1993, new management has been installed both at the OCRWM headquarters and at the Yucca Mountain Site Characterization Office. Under the leadership of the OCRWM's new director, Dr. Daniel Dreyfus, a number of modifications to the program have been initiated or proposed. An important example is the DOE's decision to aggressively pursue the development of a multipurpose container (MPC); this decision will affect all components of the waste management system.

In addition, the OCRWM is evaluating several new program strategies based on different funding levels. The OCRWM's preferred strategy, which assumes increases in funding for this fiscal year and continuing increases in future years, would bring changes in the site-characterization and licensing approach for Yucca Mountain. This new program scenario includes:

- the development and initial procurement of the MPC by 1998, which can be used for both transport and storage of spent fuel (depending on final design, these containers also may potentially be used for disposal of the spent fuel in a repository);
- the downsizing of the underground and surface-based testing programs;
- a phased-licensing approach relying on postemplacement confirmatory testing; and
- extending the period of waste retrievability from the current 50 years to 100 years.

The implications of these and other changes for the program will be evaluated by the Board as part of its ongoing technical and scientific review of the program. For the purposes of this report, however, no attempt has been made to incorporate an assessment of the effects of the potential program modifications. The following discussions are based on material that has been presented by the DOE to the Board in formal meetings or during formal interactions between DOE personnel and Board staff primarily during 1993.

Transportation and Systems

The concept of having a container or package that can be used for a combination of purposes of storage, transport, and disposal of spent fuel has been discussed or proposed since the 1980s.[1,2,3,4] The concept

1 *Westinghouse Electric Corporation. 1984. "Preliminary Cost Analysis of a Universal Package Concept in the Spent Fuel Management System," WTSD-TME-032, 1984.*

2 *Raymond E. Hoskins. 1989. "A Systems Evaluation of the High Level Nuclear Waste Management System Based on Integration of*

has been generically referred to as the universal container, or universal cask, concept. Originally, the universal cask concept consisted simply of a shielded, stand-alone cask, which, once loaded and sealed, could be used for dry storage, transport, and disposal with little or no modifications. Once loaded inside the cask, the bare spent fuel assemblies would not have to be handled again. Because of the shielding and transport accident survival requirements, the containers would be large with thick walls.

In the latter part of 1992, the Department of Energy began to assess a concept it calls the multipurpose container or canister (MPC) concept. It consists of a thin-walled container, often referred to as a canister that would hold the spent fuel assemblies but not provide shielding. This canister would require a different overpack for each of the three functions: possibly a concrete bunker for storage, a steel cask for transportation, and a third type of overpack for disposal. Once sealed inside the canister, the bare spent fuel assemblies would not have to be handled again. The canisters, when housed in their transport casks, could be shipped by rail. The DOE is considering two sizes; a large one, which when housed in its transportation cask would have a gross weight of 125 tons and a smaller one, which would have a gross weight of 75 tons. The most recent published products from this effort are the Conceptual Design Report and the draft "request for proposal" (RFP), or more precisely, a draft statement of work that would become part of an RFP (DOE 1993c).

In addition to developing these documents, the DOE convened two stakeholder meetings in 1993 — one in July and one in November — to elicit opinions about the concept from interested parties, principally from utilities and the vendor community, about the concept. At the November meeting, the DOE presented a proposed schedule for the possible development of the MPC. Some of the key milestones in the schedule include (1) early 1994 for the decision of whether to proceed with MPC development; (2) spring 1994 for the issuance of the RFP; and (3) 1998 for making the first MPCs available for use by the utilities. Between 1994 and 1998 the vender(s) would design the MPC to meet primarily the storage and transport functions of the waste management system, to obtain certification from the Nuclear Regulatory Commission for these two functions, and fabricate an initial lot.

Enthusiasm for the concept gathered momentum during 1993, and in early 1994 the DOE made the decision to proceed with the design and development for the MPC. It appears that the impetus behind this momentum is the pressure on the DOE to comply with the 1998 date in the standard contract for spent fuel acceptance.

Within this environment of heightened activities, the Board has had several opportunities to explain its views on the MPC concept and its possible implementation. In 1993, the Board was briefed on the DOE's MPC concept at two of its meetings dealing with the issue of the interim spent fuel storage. The first was the January Board meeting, which featured discussions on interim storage in a broad sense. The second was a meeting, held in early November in Dallas, Texas, sponsored jointly by the Board's panels on Transportation & Systems and on the Engineered Barrier System, that addressed specific technical issues in greater detail than was possible at the earlier meeting.

The Potential of the MPC Concept

The Board has for some time maintained an interest in the generic concept of a container that can perform multiple functions. In the past, the Board repeatedly urged the DOE to assess alternatives to its then "baseline" design concept for managing the nation's spent fuel and high-level waste. Since its *Second Re-*

Dual Purpose Cask into the System as Alternative to DOE's Proposed Monitored Retrievable Storage Facility as an Integral Part of the System," University of Tennessee, June 30, 1989.

3 *Marvin L. Smith, "Universal Storage/Transport/Disposal Packages," presented at the International High Level Waste Management Conference, Las Vegas, Nevada, April 12-16, 1992.*

4 *Electric Power Research Institute. 1993. "Feasibility Evaluation of the Universal Container System," EPRI TR-101988, February 1993.*

port to the U.S. Congress and the U.S. Secretary of Energy, the Board has expressed concern about the many handlings and transfers of spent fuel required by the baseline scenario, which called for the use of different single-purpose casks for storage, transportation, and disposal. To reduce handling and enhance safety throughout the system, the Board recommended that the DOE look at alternative technologies to reduce handling, including the concept of a universal, or multipurpose, container.

Presently, the DOE's MPC is only a concept. As a *concept*, the Board believes it offers real potential. It has the potential of addressing a number of broad issues that the Board has identified in the past. In addition to its potential for enhancing safety by reducing handling and transfers, there are other possible benefits that may accrue.

The MPC concept could substantially reduce the potential problems arising from the proliferation of different technologies. For example, as some utilities begin to run out of storage space in their spent fuel pools, they are facing the need for the dry storage of spent nuclear fuel at their reactor sites. As the need for dry storage has increased, a number of different storage systems have been installed by the utilities. The Board believes that a diversity of technologies may eventually pose compatibility problems for the civilian radioactive waste management system.

An additional advantage of the MPC concept is that, by its very nature, it may force a systems approach to waste management. If the MPC concept is developed *properly*, the DOE will have looked at the storage, transport, and disposal functions in an integrated manner. Furthermore, because developing the MPC could bring with it a link between the responsibilities of the utilities and those of the DOE, it may encourage a more active collaboration between the two parties in nuclear waste management.

Despite these advantages, however, the Board has some real concerns about how the MPC concept is being developed.

Board Concerns

The Board's first concern is that an analysis of the whole waste management system is not yet completed. The Board has consistently stated that because the functions of storage, transportation, and disposal are strongly interconnected, the DOE should use systems analysis when making decisions about different parts of the waste management system. This kind of work is a prerequisite for design, and, although some future iterations may be necessary, systems analysis should not entail a large-scale effort. Completing a systems analysis will allow the DOE to evaluate the pros and cons of alternative concepts for major parts of the waste management system.

Such an analysis would help determine, for example, if the various potentials of the MPC concept, such as safety enhancement and cost savings, can indeed be achieved in a practicable way. A systems analysis also will provide a technical basis for making decisions related to various MPC performance criteria and design features. This type of analysis should take into account aspects of the rest of the waste management system, including the MPC's effects on the design of the repository and on thermal-loading options. As was noted at the Dallas interim storage meeting at the beginning of November 1993, a complete systems analysis is not currently available, and the DOE itself acknowledged that much remains to be done in this area. At its recent meeting in January, 1994, the Board was given a briefing on DOE's System Architecture Studies and heard about the studies that support MPC evaluation. The Board was encouraged by the progress that has been made.

The Board's second concern is that the schedule for the development and implementation of the MPC concept is overly optimistic. In its March 1993 *Special Report to the U.S. Congress and the U.S. Secretary of Energy*, the Board observed that the overall civilian radioactive waste management program is being driven by unrealistic deadlines. This appears to be the case with the MPC as well. The DOE seems to be rushing to settle on a design so the MPC will be ready to meet the 1998 date for federal acceptance of spent nuclear fuel from the utilities. The Board believes, however, that specifying a design now, especially without completing the supporting systems analyses, could preclude more desirable options later on. And, if hastily made decisions result in adverse consequences that have to be mitigated, the program ultimately could be delayed or incur additional costs.

The concern about proceeding under an unrealistic schedule and incurring attendant programmatic risks is not the Board's alone. This was also a concern of most of the participants at the November 1993 MPC stakeholder workshop, especially because the DOE is now planning to request burnup credit from the Nuclear Regulatory Commission.[5] Since the NRC has never before granted burnup credit, many participants expressed the view that combining an overly optimistic schedule with the request for burnup credit during transportation container licensing could delay the timely licensing of the MPC.[6]

A third concern is that to meet the 1998 date, the disposal function is being given low priority during MPC development. This could result in a dual-purpose container that can be used only for transport and storage. The Board believes that if the disposal function is prematurely dropped, the appeal of the MPC concept will be substantially diminished. The draft RFP leads one to conclude that this is a real possibility. The requirements specified in that document relate almost exclusively to storage and transportation. It is virtually devoid of any requirement on the bidder on anything related to the disposal function.

The Board understands that many uncertainties remain about the repository and its design and that to wait until most of the disposal issues have been resolved would mean a long postponement of MPC development that would negate much of the value of the MPC concept. Nonetheless, an attempt should be made at least *to address* in a substantive way the issue of how a true multipurpose container can evolve or be implemented given what is known today and the technology that is practical today. The systems analysis work, that has already been alluded to, would be very valuable in addressing this substantive issue.

The Board has aired the thrust of these concerns on previous occasions, including at the Board's Dallas meeting on interim storage on November 1 and 2, 1993. These concerns were articulated more fully in testimony at a field hearing of the House Committee on Science and Technology, Subcommittee on Energy, held in Newport News, Virginia, which was held the week following the November meeting.[7] The Board outlined them once again in a letter from the Board to the Director of the Office of Civilian Radioactive Waste, on January 24, 1994. This letter urged the DOE to address the Board's concerns and expressed the hope that resolution of these issues would be reflected in both the timing and the content of the RFP.

Conclusions

1. If developed properly, the MPC has the potential of (1) enhancing safety in the waste management system by substantially reducing handling, (2) fostering a systems approach to the management of the nation's spent fuel and high-level waste, and (3) in-

5 To "request burnup credit" means that the DOE will ask the NRC to depart from its previous practice and allow the DOE to take into account in its MPC design the fact that the MPCs will be loaded with spent fuel, which is less reactive than fresh, unused fuel and is therefore less likely to "reach criticality" if a container should be breached during storage, transportation, or disposal. If a cask containing fuel assemblies were to be breached and were to fill with water, criticality, or a self-perpetuating nuclear chain reaction, could occur. The more burned up, or used, the fuel is, the less likely this is to happen. Receiving burnup credit has design implications for the MPC. For example, in the past, vendors seeking licensing of their spent fuel transportation casks have always been required by the NRC to adopt the conservative approach during cask design: they must design their casks assuming that the casks will be loaded with the most highly reactive fuel of all, fresh fuel.

6 At a recent technical exchange between the DOE and the NRC, NRC staff suggested that if the DOE really wants to meet the 1998 acceptance date, it should probably look for alternative MPC designs that will not require the allowance of burnup credit.

7 The Board had expressed its concern about premature specification of the MPC system on an earlier occasion in a letter dated September 30, 1993, to Senator Bennett Johnston, Chairman of the Subcommittee on Energy and Water Development, Committee on Appropriations. The letter stated that a narrow interpretation of proposed language in the appropriations bill regarding MPC development could lead to premature specification of the MPC concept that could preclude more desirable options later on.

troducing a level of standardization into a system that currently is evolving in an ad hoc fashion.

2. A systems analysis that assesses the trade-offs of alternative concepts for the major parts of the system — storage, transport, *and* disposal — and that would provide a technical basis for decision making has not been completed.

3. The current schedule for developing and implementing the MPC is overly optimistic. Rushing to meet the 1998 date for initiating federal acceptance of spent fuel from the utilities might lead to the premature specification of a design that could preclude more desirable options later or ultimately result in program delays and increased program costs.

4. Urgency about meeting the 1998 date has resulted in the disposal function of the MPC being given low priority. The Board believes that if the disposal function is prematurely eliminated, the potential of the MPC concept would be greatly diminished.

Recommendations

1. The Board recommends that the DOE complete the systems analysis necessary to support decisions about MPC development. This analysis should determine if the various potentials of the MPC concept can be achieved in a practicable way. It should also provide a technical basis for decisions related to MPC performance attributes and design features and for developing schedules and milestones.

2. To avoid prematurely dropping the disposal function, the Board recommends that DOE begin to address in a technically substantive way the issue of how a *true* multipurpose container can evolve and be implemented given what is known today and the technology that is practical today, despite all of the uncertainties associated with repository design.

Engineered Barrier System

The engineered barrier system in a potential underground repository for the disposal of spent fuel and high-level waste could consist of many parts. For example, the system could include the waste form (e.g., spent fuel assemblies or high-level waste in the form of vitrified glass logs), the waste package (which is the waste form encapsulated in one or more containers, canisters, or overpacks), filler materials inside the waste package, and any backfill material that might be used to fill the tunnels after the waste has been emplaced. The core element in the engineered barrier system (EBS), however, is the waste package. As discussed in this section, the DOE's level of activity in the area of waste package design was greatly expanded during 1993, principally to support the conceptual designs for the multipurpose canister (MPC) but also in support of the DOE's "Advanced Conceptual Design" phase of waste package design. The design of the EBS seems to be evolving to include more robust waste packages that would be placed in a drift, or tunnel, rather than slipped into a vertical borehole in a tunnel, which was the DOE's original plan. This new approach has important, positive implications for system safety as well as for the consideration of extended retrievability.

The following discussion addresses the current status of research related to the development of the waste package in the DOE's civilian radioactive waste management program. Not only does the Board continue to be concerned about the low level of research in the area of corrosion, but the Board is becoming increasingly concerned about in-repository criticality control[8] and the effects of high temperatures on the ability of zircaloy cladding to serve as a barrier.

Because of its potential effects on the entire waste management system, especially the waste package, this section begins with a brief discussion of the DOE study, completed in early 1993, of the 15 thermal limits contained in the *Site Characterization Plan*

8 *"Controlling criticality" means ensuring that a self-sustaining nuclear reaction will not take place in the repository. (See 10 CFR 60.131 (b)(7).)*

(DOE 1988) and a broader thermal-loading systems study.

Potential Thermal Limits

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.

One area of progress regarding thermal loading during fiscal year 1993 was the conclusion of a brief and informal reexamination of the 15 thermal limits contained in the DOE's *Site Characterization Plan* (SCP). The reexamination took place during a two-month period via informal discussions among project personnel but involved no experimental work and apparently limited literature survey or analytical efforts. The principal objectives of the reexamination were to determine if the 15 thermal limits were still valid, and whether they were valid for *all* emplacement modes, not just the vertical borehole emplacement mode in the SCP.

The reexamination resulted in recommendations to retain certain thermal limits and to drop, add, or change others. The 350°C zircaloy cladding temperature limit, which is discussed in more detail below, was one of the 15 thermal limits reexamined. The recommendation was to retain it unchanged.

The reexamination of the 15 thermal limits was part of a broader repository-level system study on thermal loading begun by the DOE in 1993. 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 emplacement 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. Other problems include determining the extent of the "disturbed zone,"[9] the duration of the performance monitoring program, the size of the area to be characterized, and changes in research needs as functions of thermal loading. The Board is looking forward to the results of this broader repository-level system study.

The Multipurpose Canister

As described in the previous section on the activities of the Panel on Transportation & Systems, DOE personnel initiated an effort in 1992 to examine the feasibility of a concept they call the multipurpose canister (MPC). This concept is one of a family of concepts — known variously as universal containers or multipurpose casks — that have as their hallmark the *permanent* sealing of spent fuel in a container at the reactor where the spent fuel was generated. Because they would not be reopened, universal container concepts have the potential to increase system safety and decrease system costs. In its *Sixth Report*, the Board urged the DOE to study such concepts.

As part of its examination of the feasibility of the MPC concept, the DOE produced several MPC conceptual designs, the largest of which can hold 21 spent fuel assemblies from pressurized water reactors (PWR). Since, in general, the greater the capacity of a waste package, the more attractive it becomes from safety and cost standpoints, it is important to understand the assumptions the DOE used to reach a waste package design that limits its capacity to 21 PWR assemblies.[10]

9 *The "disturbed zone" comprises those areas surrounding the repository drifts in which the physical and chemical properties may change significantly as a result of repository construction or radioactive decay heat. See 10 CFR 60 for a more complete definition.*

10 *Unless otherwise indicated, the use of the word "assemblies" in this discussion refers to spent fuel assemblies taken from pressurized-water reactors. Approximately two-thirds of U.S. civilian power reactors are pressurized-water reactors (PWRs); the others are boiling-water reactors (BWRs). BWR fuel assemblies are smaller than PWR assemblies (e.g., about 40 BWR assemblies*

If one assumes that entrances to the repository from the surface for the purpose of emplacing (or retrieving) waste packages are low-angle ramps and that waste package disposal overpacks will be brought to the repository intact via the nation's rail system — then there do not appear to be any reasonable repository-related limits to the physical dimensions or weight of a waste package. The repository can be engineered to accommodate a waste package of any size and weight that can be handled by the storage and transportation components of the nation's radioactive waste management system.

Of crucial importance under the assumptions specified by the DOE for its MPC conceptual design is the effect of the heat generated by radioactive decay on the temperatures inside the waste package and in the repository. The effect of this heat is to constrain the DOE's MPC design to a capacity of 21 assemblies to meet the 350°C zircaloy cladding temperature limit. (See discussion of zircaloy cladding below.) The DOE recently completed a brief study showing that the capacity limit is *directly attributable to* the assumption of 10-year-old spent fuel and the assumption that the aging of spent fuel would not be allowed.[11] However, relaxing either of these assumptions would lead to an MPC with a greater capacity. The Board believes it is very important that the DOE continue to evaluate the potential effects of these and *all other* assumptions used for MPC conceptual designs on waste package cost, performance, safety, and any other aspects of the waste management system that might be affected.

Advanced Conceptual Design

The waste packages and the repository are linked inextricably by the extensive interactions between them, particularly thermal interactions. Beginning in fiscal year 1993, the waste package and repository design efforts entered a new phase, which the DOE calls "Advanced Conceptual Design" (ACD). The purpose of this phase is to produce and evaluate waste package and repository conceptual designs leading to the selection of one or two to carry into the next phase, called "License Application Design." Throughout fiscal year 1993, the major focus of the DOE's Advanced Conceptual Design activities was supporting, primarily, MPC conceptual studies and, secondarily, efforts to design the underground exploratory studies facility. As part of this effort, the DOE looked at a number of issues including criticality control, potential effects of tunnel size on waste package temperature, as well as waste package materials and corrosion.

Criticality control

During fiscal year 1993 as a part of ACD, the DOE began to take a hard look at potential long-term issues related to criticality control after emplacement of waste packages in a repository. Both designing waste packages to achieve acceptable criticality control and analyses of such designs to establish their acceptability will likely require much effort and lengthy processes. For example, current NRC regulations for in-repository criticality control have no explicit time limit; this implies that criticality control over periods of tens of thousands of years requires modeling. And the neutron capture reactions of actinides and the long-term radioactive decay patterns of actinides, although well known, are quite complex, making them burdensome to model. To complicate things even more, predicting the long-term physical integrity of a waste package and its contents is not easy. It will be difficult to predict, for example, how the waste package contents may become rearranged as a result of phenomena such as rockfalls or long-term corrosion. The DOE should continue, if not increase, its efforts in the important area of in-repository criticality control.

would fit in the same container that could hold 21 PWR assemblies). In general, PWR fuel has higher initial enrichment in ^{235}U than BWR fuel. Thus, relative to BWR spent fuel, PWR spent fuel tends to emit more heat per ton of fuel. In general, therefore, PWR spent fuel assemblies become the limiting case for designing the multipurpose canisters.

11 *Milner, R. A. December 23, 1993, letter to the Board.*

Tunnel diameter

Also as part of ACD, repository program personnel performed a brief modeling study on the effect of tunnel diameter on waste package temperature for various thermal-loading strategies. The results of this study seem to indicate that drift diameter might be important for peak internal waste package temperatures only for very high 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. For example, if placed in a 14-ft-diameter tunnel, a waste package would reach a maximum internal temperature approximately 25°C higher than if placed in a 25-ft-diameter tunnel (this assumes in-drift emplacement, a 21-assembly waste package, and a repository thermal loading of 114 kw / acre using 22-year-old fuel, a very high thermal loading). The maximum temperature difference (25°C) between the two tunnel diameter cases would be reached about 10 years after emplacement, then taper off to about 10°C 50 years later. The maximum waste package internal temperature for the narrower drift was almost 350°C.

However, the results of this modeling study represent only one scenario, a very high thermal-loading strategy. If the modeling were repeated under a different scenario, for example, with a lower thermal loading, say 100 kW / acre rather than 114 kW / acre, and the lower thermal loading were accomplished by increasing the spacing between waste packages in a drift, with everything else being equal, one would expect the peak internal temperatures to be lower for the same drift diameters because each package would have more rock wall to which to spread its heat. Furthermore, the difference between peak internal temperatures as a function of drift diameter should also 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.[12]

Materials/corrosion

Currently, the DOE is focusing on multibarrier waste package designs that, according to investigators, have inner metal barriers that are “corrosion-resistant” while the outer metal barriers are made of a “corrosion-allowance” material. (Alloy 825, a high-nickel alloy, is an example of a corrosion-resistant material, while ordinary carbon steel is an example of a corrosion-allowance material.) Not only would the outer barrier protect the inner barrier, but products from the inevitable corrosion of the outer barrier could provide physical protection to the inner barrier as well as creating an electrochemical environment favorable for protecting the inner barrier against corrosion. In this latter case, the outer barrier need not be continuous to be protective. Furthermore, the inner and outer barriers would corrode by different mechanisms. Although the Board does not disagree with the DOE’s current focus, there are other multibarrier alternatives. It is hoped that the DOE will investigate some of these during its Advanced Conceptual Design phase. As a minimum, the DOE must produce a reasoned justification as to why the approach with a corrosion-resistant metal barrier inside and a corrosion-allowance metal barrier outside is among the better multibarrier approaches.

SCP Conceptual Design Out of Date

Since the SCP Conceptual Design Report (SCP-CDR)[13] was issued in 1987 (DOE 1987) and especially during the last two years, many fundamental changes in basic waste-package and repository concepts have emerged. For example, the following changes now are among the leading concepts for waste-package and repository design:

12 *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.*

13 *The waste package design in the SCP-CDR was incorporated by reference from the Site Characterization Plan then in preparation.*

- long-lived, high-capacity, robust waste packages rather than the short-lived, low-capacity, thin-wall waste package of the SCP-CDR;

- in-drift rather than borehole emplacement of waste packages;

- thermal-loading strategies considerably different from the limited-duration thermal "pulse" (57 kW/acre and 10-year-old spent fuel) of the SCP-CDR;

- repository capacity considerably greater than contemplated in the SCP-CDR, if only because of project delays and the concomitantly lower heat generation rate of the older waste at time of emplacement;

- use of shafts only for ventilation intake or exhaust with all movement of humans and materials by wheeled (or tracked) vehicles on low-angle ramps rather than weight-limited hoists;

- possibility of tunnels with considerably smaller diameters than those contemplated in the SCP-CDR (except for the portal-to-portal main tunnel).

Baseline designs, such as the waste package and repository designs in the SCP-CDR, can be valuable. In addition to establishing theoretical feasibility and helping identify data needs, they are important and necessary communication and management control tools. However, when the changes to them become so numerous and significant that the baseline designs are clearly obsolete, their continued use becomes both a hindrance and an unnecessary cost. In consultation with the Nuclear Regulatory Commission (NRC), the DOE should formally change the waste package and repository baseline designs to bring them into line with current thinking.[14] This should be done early during the DOE's Advanced Conceptual Design phase. The DOE has had formal procedures for considering and approving changes to project documents for some time. These procedures could be used to make the necessary changes to the baseline designs.

Extended Retrievability in a Geologic Repository

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. It does not mean infinite retrievability. The idea of extended retrievability is not new.[15] 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.

The concept of extended retrievability also carries with it the connotation that retrieval would be relatively safe, simple, and inexpensive and that it could be accomplished reasonably quickly. The concept is especially suited to an unsaturated site, such as the Yucca Mountain site, since there should be no need to pump water out prior to retrieval as there could well be with a saturated repository. Furthermore, an unsaturated site needs neither backfill nor shaft sealing to keep water away from the packages or to prevent nongaseous radionuclides from migrating into the surrounding environment (Hackbarth 1985).

The Board encourages the DOE to examine seriously the principle of extended retrievability and to avoid decisions that could forestall implementation of the concept. To determine a specific extended retrievability period for planning purposes, the DOE

14 On March 10, 1994, at a meeting of the Board's Panel of the Engineered Barrier System in Pleasanton, California, the DOE announced that it had adopted the MPC as the technical baseline. It appears this may be a step in the same direction as the Board is recommending.

15 For example, see Roseboom, E. H., Jr. 1983. Disposal of High-Level Nuclear Waste Above the Water Table in Arid Regions, Geological Survey Circular 903, 1983, and Ramspott, L. D. 1991. "The Underground Retrievable Storage (URS) High-Level Waste Management Concept," in Proceedings of the Symposium on Waste Management, Tucson, Arizona, February 24-28, 1991.

should examine the concept of extended retrievability and assess its potential incremental costs, safety issues, and benefits for various periods.

Waste Package Research

The Board remains concerned about the very limited level of materials research being carried out by the DOE as part of its waste package design program. More work needs to be done in a number of areas. One area that has been neglected is research into the long-term corrosion performance of waste package materials. Many years of careful laboratory experimentation at ambient and moderately elevated temperatures will be needed to validate predictions of the corrosion performance of waste packages over thousands of years with confidence. This is particularly true for modern materials such as stainless steels and nickel alloys, which have an industrial experience base only a tiny fraction of the lifetimes envisioned as requisite for a repository.

Also, now that the MPCs may be deployed soon (the target date is 1998), the DOE needs to recommence and accelerate research on metal joining and on methods for the nondestructive evaluation of metals and welds. Such research is necessary to ensure that the MPC structure is able to carry out its containment and criticality control functions during disposal.

Assuming waste packages with outer walls of corrosion-allowance material and inner walls of corrosion-resistant material, as long as the outer wall is kept dry[16] and below about 300°C, the only form of corrosion should be low-temperature oxidation — a slow process for any of the waste package metals under consideration. From an oxidation standpoint, one could postulate (by extrapolation of high-temperature data) that 10 cm of ordinary carbon steel would last longer than 10,000 years in a dry environment. But extrapolation of high-temperature data alone may not provide sufficient confidence about low-temperature oxidation rates. Some data are needed in the temperature range of interest to confirm the extrapolation. The Board is gratified that the DOE has acquired the necessary apparatus and will begin obtaining the necessary data on low-temperature oxidation in 1994.[17]

Waste-package fillers

The concept of waste-package fillers (solid materials for partially or totally filling void spaces in waste packages loaded with spent fuel) is well recognized. Properly used, it is conceivable that fillers could promote heat transfer, serve as an additional short- and long-term criticality control measure, provide support or cushioning to assemblies during motion, retard the movement of water and oxygen to the assemblies and the migration of radionuclides from the assemblies, serve as "getters" that would chemically react with or adsorb radionuclide-containing species such as $^{14}CO_2$ and ^{129}I, and provide an electrochemical environment that could slow internal corrosion. On the other hand, fillers will add cost and weight and, if added at utilities, will impose a greater demand on a diverse work force. And some fillers could have detrimental effects, such as reducing heat transfer or increasing stress on assemblies. Moreover, some fillers could have a tendency to shift and settle, which would increase the difficulty of predicting their performance. Some consideration needs to be given soon, however, to how and where fillers, if used, could be incorporated into waste packages, and how loaded MPCs without fillers could be retrofitted.

Although the DOE has indicated awareness of the potential advantages and disadvantages of fillers, it has not evaluated them and apparently has no formal plans for such an evaluation according to the recently issued *Waste Package Plan* (DOE 1993b) and *Waste Package Implementation Plan* (DOE 1993a). The Board believes that this is unfortunate because it could mean that insufficient work will have been done to incorporate fillers into the initial deployment of MPCs or to support the decision to forego their use.

16 Here, "dry" means not only the absence of liquid water, but also a relative humidity that is not elevated.

17 The apparatus is a CAHN TG-131 ultrasensitive thermogravimetric analyzer located at Lawrence Livermore National Laboratory.

Zircaloy cladding

Zircaloy cladding[18] has the potential to be a superior barrier in a true multibarrier waste package. It is a corrosion-resistant material, and, because it has a different composition from the corrosion-resistant materials under consideration for the waste package (e.g., Alloy 825), its failure may require a different mechanism. In general, the more mechanisms required to achieve waste package failure, the more robust the package will be. However, the price of using zircaloy cladding as a barrier may be high. To protect the integrity of zircaloy cladding so that it might function as a barrier, a 350°C cladding temperature limit was established in the SCP. Because of the 350°C limit, however, waste packages with capacities of more than 21 assemblies could be excluded from the waste management system.

The topic of zircaloy cladding and its potential contribution to the long-term performance of the waste package should be revisited. In particular, the technical trade-offs of whether the zircaloy cladding should be a barrier need to be addressed. In the absence of studies, the Board's initial inclination is that it should be considered a barrier. This could readily change, however, if it were shown that adopting it as a barrier would result in cost increases without increases in safety.[19]

Conclusions

In general, the past year has been one of progress in the area of waste package design, although much remains to be done. Some progress has been made in the area of waste package research, also, but much less than the Board believes is appropriate. The Board has reached the following conclusions in both areas:

1. Design of waste packages for criticality control and analyses of those designs to ensure long-term criticality control of emplaced waste packages will require much effort and could be a lengthy process.

2. There have been so many changes to the waste package and repository baseline designs of the SCP that those designs are obsolete.

3. The concept of extended retrievability for a geologic repository is very attractive and strongly merits its further consideration and analysis.

4. Research on metal joining and on the nondestructive evaluation of metals and welds, as well as the potential effects of long-term corrosion on waste package materials, has received relatively low priority during recent years. This is disturbing particularly since MPCs may be deployed soon.

5. The DOE has not evaluated the use of waste-package fillers and has only begun evaluation of the potential role of zircaloy cladding as a barrier.

Recommendations

1. The DOE should continue and extend its examination of the assumptions used for its MPC conceptual designs, ensuring that the examination includes *all* of its design assumptions. The potential effects of these assumptions on waste package maximum capacity as well as on waste package performance, safety, and costs should be carefully evaluated.

2. In consultation with the NRC, the DOE should change the baseline designs for the repository and the waste package to reflect current thinking.

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18 Spent fuel assemblies consist of an array of spent fuel rods. Each rod is encased in a cladding. Almost all of the cladding is zircaloy, an alloy consisting mostly of zirconium.

19 Some spent fuel may be stored in dry storage at reactors for prolonged periods. It is conceivable that the high temperatures experienced during prolonged dry storage could materially reduce the subsequent lifetime of zircaloy as a barrier in a repository. Therefore any study of zircaloy as an in-repository barrier should include examination of the effects of prolonged dry storage on zircaloy performance.

At a meeting of the Panel on the Engineered Barrier System on March 10, 1994, in Pleasanton, California, the DOE described analytical efforts on zircaloy cladding carried out in 1993. These efforts appear to be confirming the promise of zircaloy cladding as a barrier and should be continued.

3. The Board encourages the DOE to examine seriously the principle of extended retrievability for a geologic repository and to avoid designs and decisions that could forestall implementation of the concept.

4. The DOE should develop plans for examining fillers. Even if specific filler materials are not selected until later, methods for using or retrofitting with fillers in the perhaps soon-to-be-deployed MPCs should be developed now.

5. The DOE should continue to examine the role of zircaloy cladding as a barrier and should recommence and accelerate research on metal joining and nondestructive evaluation of metals and welds.

Structural Geology and Geoengineering

Panel input in this section relates to geoengineering and addresses primarily the status of the site-characterization program since the release of the Board's eighth report, *Underground Exploration and Testing at Yucca Mountain* (NWTRB 1993b).

Site Characterization — Status of the Surface and Underground Programs

Site-characterization will help reveal whether or not the site at Yucca Mountain is suitable for hosting a deep geologic repository; it also is critical for gathering data to help design the proposed repository, which must be able to isolate radionuclides for thousands of years. *Surface-based* dry drilling and testing and exploration and testing in the *underground* exploratory facility are the two major components of the DOE's site-characterization project at Yucca Mountain, Nevada. Exploration and testing from both the surface and the underground studies facility will provide most of the three-dimensional information about the site, including the stratigraphy and disposition of faults. Data from the site will be used in models, which will be used to predict the future behavior of the geology of the site.

Currently the site-characterization project consists of a number of study plans, many of which depend on the proper execution of surface and underground testing to ensure that the observations, samples, or measurements are taken correctly and in the right time frame. Because of the complexity, duration, and expense of the program, both surface-based and underground exploration and testing require extensive planning and scheduling to be effective. However, OCRWM management decisions about how to allocate funds have delayed the initiation of underground excavation for the exploratory facility and slowed progress in surface-based activities. As a result, underground exploration and testing from the exploratory facility has not yet begun, and the surface-based dry drilling and testing program is still in its early stages.[20] The Board is encouraged that activities at the site have increased and hopes that the momentum of these activities will not be slowed. However, the Board remains concerned about the potential for further delays. The following discussion addresses in more detail the challenges facing the site-characterization program.

Surface-based dry drilling

A major concern for progress in the site-characterization effort is the slow headway being made in the deep dry-drilling program. Because of a relative lack of progress and the high costs of the LM-300 drilling rig,[21] the surface-based dry drilling program has the potential for becoming a bottleneck for the entire program. Deep drilling at the site and in the vicinity of the water table has been under way since the 1980s, but after ten months of drilling, only one

20 The 200-foot starter tunnel for the tunnel boring machine has been completed and the first test alcove constructed at the end of the starter tunnel, but excavation of the facility is not scheduled to begin until August 1994. The second of an estimated 40 surface-based, deep, dry-drilled boreholes is nearing completion.

21 The OCRWM contracted to have a large prototype drilling rig, the LM-300, developed and built for use at the site. The rig is designed based on principles used in the drilling industry, but is about three times larger than any mining drill rig. It uses circulating air, rather than a liquid, within a dual-wall drilling pipe to carry cuttings to the surface to avoid contaminating or drying out the borehole walls.

borehole has been completed using dry drilling — UZ-16 in March 1993. A second deep, dry-drilled borehole (UZ-14), scheduled for completion in November 1993, has yet to be completed.

The Yucca Mountain project is faced with a dilemma regarding the dry-drilling program. At the current rate of progress and assuming one drill rig with one crew working five days per week, it will take 28.6 years to complete the planned 40 deep boreholes (cumulative length of 100,000 feet). Were four crews to operate the LM-300 seven days per week, the time would drop to 7.1 years.[22]

The OCRWM recognizes this problem and is considering a number of options. For example, the OCRWM already has conducted a drilling and testing consolidation study during the past year to reduce the amount of necessary drilling, in part, by making better use of each drillhole. Site geologists are now routinely being asked to predict the stratigraphy in a borehole before it is drilled. Hydrologists have begun predicting what hydrologic properties will be encountered before drillholes are begun. In addition, techniques for drilling faster (using improved corebits and reducing drill-stem vibration effects that limit rotational rates of the drill) are being researched. Also, the OCRWM currently is considering a proposal to join Nye County, Nevada, in a cooperative dry-drilling demonstration program in which faster, less costly drilling might be done by commercial drillers using hammer-drilling, rather than by continuous coring and reaming, as performed by the LM-300.[23] Nye County intends to explore different and less costly contractual arrangements and possibly negotiate more cost-effective work rules with commercial drillers.[24] Another possible solution, which has not been fully examined, is eliminating drillcore or boreholes that are not critical or for which tunnel- or alcove-derived data can be substituted.[25] A way should be found to estimate how much more of a particular type of data is required to make predictions using the present data and models.[26]

In its April 1992 presentation to the Board, the OCRWM stated that, because sufficient progress is not being made with the LM-300, it would need to purchase *three additional drill rigs*. But with the high cost of a LM-300 and support equipment and the annual operating cost for one-shift operation (approximately $5.6 million),[27] the Board believes serious consideration should be given to other options for making progress in the program, including the use of commercial drilling companies and drill rigs. The DOE would then be in the position of buying drillcore, rather than additional drill rigs, most probably at a greatly reduced cost.

One possible tool that could be used to help determine what data are important and thus what methods will most readily achieve the desired data is performance assessment. Iterative performance assessment can help answer important questions, such as which geologic processes are most important; how well must the processes be understood and at what level of detail; and how much data are needed (e.g., from both drillcore and boreholes and both surface-based and underground). At its present stage of development, total system performance assessment models are by necessity somewhat simplistic and therefore may not capture important details. For example, water movement in the unsaturated zone generally is now modeled as one-dimensional,

22 *Total costs, however, would increase from $151.6 million to $184.2 million, with yearly operating costs rising from $5.3 to 29.5 million. J.R. Dyer, DOE, presentation to the Board, October 19, 1993.*

23 *Although some tests require core, including tests for hydrologic parameters, water saturation, and water potential, many properties can be tested accurately using rock chips.*

24 *The county plans to conduct their demonstration drilling of up to four drill holes off the Yucca Mountain site if the DOE declines participation in the cooperative agreement.*

25 *Although some scientists agree with this approach, some maintain that it is too early to decide what dry core drilling can be reduced or eliminated.*

26 *The systematic drilling program, which plans the dry-drilling of 12 deep holes at the repository site, will use this predictive mode and apply it to three-dimensional models of the geology and the rock characteristics, including hydrological properties.*

27 *REECo, November 5, 1993, cost estimate.*

constant velocity flow with the effects of multidimensional transient flow being incorporated by grossly simplified assumptions. However, the level of detail needed in understanding such flow may be influenced by its impact on total system performance. There has to be continuous feedback to determine both the need to refine the understanding of fundamental processes and the need to refine the more abstract total system performance model.

According to the OCRWM, the relationships among the major components of site characterization including surface-based testing and underground exploration and testing, as well as repository and waste package design, site-investigation submodels and models, and performance assessment are becoming more explicit. The OCRWM is carrying out long-range, annual, and near-term test planning, with correspondingly more detailed schedules and links to final products. Iterative performance assessment will help integrate these various elements even more.

The Board encourages current efforts to refine and advance the performance assessment process. If such an iterative process with continuous feedback is implemented with rigor, it will be the means not only to guide the major elements of the program, but also to answer more specific questions such as how much more data, and consequently drillcore and boreholes, are needed for a particular submodel or model.

Excavation of the underground exploratory facility

The exploratory studies facility, which was first outlined in the DOE's *Site Characterization Plan* published in 1988, is the primary underground exploration and testing facility for the Yucca Mountain site. It has changed significantly since its original conception.[28] Increased emphasis now is being placed on exploring across major geologic structures (i.e., unit contacts, faults) at both the repository level and in the underlying Calico Hills.

Although, the new exploratory facility configuration provides for the exploration that had been recommended by the Board, it also calls for large tunnel diameters (25-ft), the simultaneous use of four full-face tunnel boring machines to excavate the facility, and extensive surface and portal facilities and underground utilities all apparently to be funded by a large increase in the OCRWM annual budget, which the OCRWM has requested for fiscal year 1995. To maintain the 2001 date for license application, the OCRWM said it planned to accelerate exploration and testing schedules in future years.[29] As a result, no formal change was made in the license application date. However, as the Board pointed out in its October 1993 report, the interference caused by the planned multiple, simultaneous operations within the underground facility would most like result in inefficient and costly operations. As underground excavation continued to be delayed, these plans became increasingly unrealistic. Despite this, the license application date (2001) has remained unchanged, adding more urgency to the program.

In fiscal year 1993, the OCRWM placed renewed priority on gaining access to the underground. Plans called for a single tunnel boring machine to excavate the initial portion of the underground exploratory facility, the portal-to-portal main loop from the north portal through the proposed repository level to the

28 *The original plan showed the ESF concentrated in the north-east corner of the proposed repository block and was to be excavated by drill and blast techniques. Access was to be provided by two shafts excavated to the repository level at a depth of 1,055 feet. The main test level (later to be called the core test area) at the repository level included 4,000 ft of intersecting tunnels. Exploration was to consist of 5,600 feet of tunneling at the repository level, extending to anticipated faults in the north-east corner of the site.*

Current plans call for tunnel accesses and the use of mechanical excavation (tunnel boring machines) and for 76,000 ft of tunneling at the proposed repository level, (i.e., the Topopah Springs formation) and in the lower Calico Hills formation; lateral drifts are planned at both levels to the Imbricate, Ghost Dance, and Solitario Canyon fault zones. The core test area is now 9,000 ft (an increase from 4,000 ft) of intersecting tunnels. Eighty-eight test alcoves are to be excavated along the access ramps and exploratory drifts for both the Topopah Spring and Calico Hills formations, providing a considerably expanded test area. (NWTRB 1993b)

29 *The large tunnels, the large number of test alcoves, and extensive surface and underground facilities and utilities were designed to support multiple and simultaneous excavation and testing operations.*

south portal. This tunnel would provide access to geologic unit contacts and major fault zones and expose typical rock conditions at and above the repository level. And, by continuing to prioritize testing within the underground facility and by separating, to the degree possible, construction activities from testing activities, the OCRWM would be able to eliminate many planned simultaneous activities. The Board supported this more focused effort and offered additional suggestions for improving the efficiency of the excavation in its October 1993 report on underground exploration and testing at Yucca Mountain.

A tunneling contractor experienced in the use of tunnel boring machines has been selected, and the delivery of a 25-ft tunnel boring machine is scheduled for April 1994, with operations to begin in late summer 1994. Once the tunnel boring machine operations have begun, the OCRWM has said it would run it without interruption, except for those cases where data would be irretrievably lost. In addition, according to the plans, surface and portal facilities and underground utilities have been greatly simplified to reduce costs. All exploratory tunnels beyond the portal-to-portal loop, as well as the core test area, are to be excavated using a small-diameter tunnel boring machine.

Although the Board has been encouraged with the changes that have taken place during the past year in the design of the ESF, it remains concerned about potential delays in the construction of the ESF. For example, the tunnel boring machine is scheduled to begin excavation in August or September 1994 with completion of the portal-to-portal loop expected by May 1996; however, all activities proposed beyond October 1, 1994 (i.e., beginning of fiscal year 1995) are currently based on the assumption that $110 million will be provided for ESF activities for fiscal years 1995, 1996, and 1997 (fiscal year 1994 funding is $55 million). Despite recommendations from the Board (December 1991 and June 1992), the DOE has *not* developed any plans or schedules for activities beyond October 1, 1994, to reflect the possibility of continued level funding. The Board concludes that this lack in planning and integration result from problems at the management level.

The DOE has stated that if the fiscal year 1995 budget is not greatly increased, the program must be restructured.[30] In its *Letter Report*, the Board stated that regardless of the funding level, the program should be structured to ensure that critical site-characterization activities be funded adequately and dependably.

More recently, since the transfer of all design activities for the exploratory facility to the management and operating (M&O) contractor, additional questions have arisen about overall program progress. For example, the length of time required to complete the portal-to-portal loop has now expanded to 24 months,[31] with further delays a real possibility. It appears that keeping the excavation of the exploratory facility on schedule will be difficult. In addition, many of the design and construction efficiencies[32] developed by the previous contractor seem to have been lost in the transfer of design activities to the M&O. Finally, the Board's recommendation for the project to incorporate standard underground construction industry practices appears to have been completely ignored.[33]

There are other reasons why the Board is concerned about delays. A request for proposals for a second tunnel boring machine and an as yet unspecified main test area excavator are to be issued in May 1994, with awards to be made in October 1994. (This would allow thermal testing to start in the core test area by mid-1997.[34]) However, if funding is not forthcoming as expected, acquisition of the second

30 *Dr. Dan Dreyfus, presentation at the Board's January 1994 meeting.*

31 *Using typical industry standards, the loop should require only approximately one year (NWTRB 1993b).*

32 *Examples include the deferral of a decision to purchase a conveyer to support machine operations and the decision not to operate the machine using a multiple-shift operation.*

33 *For example, the OCRWM should avoid cost-plus contracts and multiple operations from a single portal, as well allowing the construction contractor to define and purchase the excavation equipment. (NWTRB 1993b).*

tunnel boring machine and other equipment will likely be postponed again thus further delaying excavation of the core test area and the initiation of in-situ thermal testing.

Plans for testing in the underground facility

Extensive exploration and testing will be conducted in the underground exploratory facility. According to the OCRWM, the objectives of the underground exploration and testing program are to

- provide a unique and complementary suite of investigations meeting site-characterization and site-suitability requirements;

- provide otherwise unobtainable data regarding major geologic features (unit contacts, faults) above, at, and below the proposed repository level;

- allow a process and timing for water and gas movement throughout the geologic block;

- examine the in-situ effects of imposed conditions (excavation, thermal loading) on the natural geologic structure and function; allow a continuous, early look at the natural system to assess site suitability and provide critical design support;

- provide underground access to specific features and geologic media for conducting various in-situ, large-scale and long-term thermal, hydrologic, corrosion, and mechanical tests.

To meet these objectives, a suite of 42 tests were defined by the OCRWM in 1992. Perhaps the most important set of underground tests are part of the Unsaturated Zone Percolation Test Plan, which consists of eight separate tests.[35] The objectives of this plan are to characterize the hydrologic conditions of the unsaturated zone as well as the spatial distribution of present-day fluid, gas, and vapor flow. Data will be used to estimate ground-water travel time, predict radionuclide migration, and help design the proposed repository system (including, for example, the waste package, and repository seals). These tests appear to be well defined, particularly those that will be conducted as part of the excavation process, and the DOE appears to understand the importance of minimizing interruptions to the tunnel boring machine.[36]

However, plans for thermal testing in the underground core test area have not been adequately developed. If the core test area is to be excavated beginning in mid-1996, then details for the thermal testing planned for the core test area are needed now to help define how to best excavate the thermal test area, and procurement for a small-diameter tunnel boring machine should begin this fiscal year.[37] A test plan is necessary before the design of the core test area can be finalized, and repository and waste package conceptual designs also are required. Although waste package conceptual design activities are under way, the development of a repository conceptual design, considering both high and low thermal loading options, appears to be in its infancy.

The DOE is proceeding with a large block heater test at Fran Ridge, on the surface, near Yucca Mountain. The block, which is to be approximately 10-ft by 10-ft and 15-ft high, is being cut from a surface outcrop of Topopah Spring welded tuff. The large block test is defined as a scaled test (i.e., not an in-situ test) with the purpose of developing thermal testing equipment and possibly gaining some insight to coupled processes in a host rock containing some interconnected multiple fractures. Since the termination of in-situ thermal testing in G-Tunnel in 1989, this will be the first testing to obtain insight into the effects of high thermal loads on a potential repository system. Although useful, this large block test will not eliminate the need for in-situ (i.e., underground) testing, which will be required to validate data being used in

34 *ESF draft preliminary schedule, dated October 29, 1993.*

35 *Perched-water tests, hydrologic properties of major faults, intact-fracture tests, percolation tests, bulk permeability tests, radial borehole tests, excavation effects tests, and hydrochemistry tests.*

36 *Standby costs of an idle tunnel boring machine are estimated to be approximately $60,000 per day for a three-shift operation*

37 *The Board recommended that the DOE allow the construction contractor to obtain the needed equipment through lease or purchase.*

numerical models. These underground tests would be aimed at understanding important phenomena, such as the movement of heat through the rock as a result of buoyant convection, and to make decisions about thermal loading, waste package emplacement, and waste package design. The Board is left with the conclusion that integration is lacking among those working on plans for underground in-situ thermal testing, repository design, and waste package development.

Conclusions

1. There appears to be no simple way to improve the progress and reduce the costs of the deep dry-drilling program at Yucca Mountain. Most likely, a number of approaches will be required including increasing LM-300 drilling efficiency by allocating more money to drilling and perhaps using different drill rigs. Using performance assessment is probably the most valuable way to link the amount of drillcore and boreholes needed to specific data needs.

2. Continued surface-based testing and the quick completion of the portal-to-portal loop through Yucca Mountain would help resolve existing uncertainties and help set future site-characterization activities by providing data to develop models and undertake iterative performance assessment.

3. It appears that maintaining a timely and cost efficient schedule for operating the tunnel boring machine and completing the portal-to-portal loop will be very difficult. The schedule for beginning tunnel boring machine operations continues to slip, and the estimated time it will take to excavate the portal-to-portal loop is now almost double what it should be.

4. Further delays in the program's underground in-situ thermal testing schedule are a serious possibility, and plans for thermal testing in the core test area have not been adequately developed. However, a test plan, as well as repository and waste package conceptual designs are required before the design of the core test area can be finalized. Although waste package conceptual design activities are under way, the development of a repository conceptual design that considers both high and low thermal-loading options, appears to be in its infancy.

5. Integration are lacking among those working on thermal testing plans, repository design, and waste package development.

Recommendations

1. The Board continues to encourage the DOE to operate the tunnel boring machine as continuously as possible while excavating the portal-to-portal main loop. Machine operations should be delayed only to recover those data that otherwise would be irretrievably lost.

2. Regardless of the funding level, the program should be restructured to ensure that critical site-characterization activities be funded adequately and dependably.

3. The Board recommends that the DOE develop a contingency plan and schedule for the site-characterization project that reflects a relatively level budget. *The plan should favor activities critical to determining the suitability of the site, incorporate a rigorous prioritization of activities, and encourage a greater sensitivity to cost control by the DOE and its contractors.* In the event that the budget is increased, a well-defined plan will provide a good basis for expanding site-characterization efforts.

4. The Board recommends that the DOE consider hiring commercial drilling companies to provide the needed drilling capacity in lieu of purchasing additional LM-300 drill rigs.

Risk and Performance Analysis

Beginning with its *First Report*, the Board has recognized that many critical issues associated with the assessment of Yucca Mountain cannot be resolved by data collection alone. Inherent uncertainties associated with the geologic system and with predicting performance for thousands of years require the substantial input of *expert judgment*.[38] Such judgment, for example, could be that of a hydrologist determining the applicability of a given theoretical ground-water flow model to the unsaturated zone around Yucca Mountain, that of a metallurgist in extrapolating short-term corrosion data to probable waste package behavior over 10,000 years, or that of a manager weighing the effects of unresolved uncertainties upon repository licensing. Judgment is used extensively by scientists, engineers, and managers in their day-to-day activities. More often than not this is done informally and in a non-explicit manner. The Board's focus in this and in past reports has been on the use of *explicit, formally elicited* expert judgment by the DOE and its contractors in programmatic studies and in performance assessment.

In programmatic studies expert judgment has been used to aid the DOE in reaching important decisions regarding the waste program. In the *Exploratory Studies Facility (ESF) Alternatives Study*, for example, different configurations of the facility were evaluated, while in the Calico Hills Risk / Benefit Analysis, the benefits of tunneling into the Calico Hills formation beneath Yucca Mountain were weighed against the risks of such exploration degrading the performance of a possible future repository. These studies used a structured approach called *decision analysis*.[39]

In performance assessment, the initial goal may be to aid in DOE decision making, but ultimately, regulatory compliance and demonstration of that compliance will be the dominant concern. The determination of regulatory compliance will take place in highly contested hearings in front of licensing boards. Although high-quality expert judgment is necessary for both programmatic and compliance decisions, legal issues and precedence regarding the admissibility of expert judgment are also of interest for the latter.

The Board's concerns about the DOE's use of expert judgment have centered about methodology, the need to incorporate expertise outside of the DOE and its contractors, and the need for the DOE and the NRC to achieve greater agreement on the process and potential use of expert judgment prior to the beginning of the licensing process. In its *Fourth Report*, the Board recommended that the DOE hold a workshop on expert judgment and as a result, propose specific recommendations for improvements in its future use. On November 18-20, the DOE held a workshop on the use of expert judgment in decision making in Albuquerque, New Mexico. More than 100 people from the DOE, its contractors, other government agencies, and the professional and academic community attended.

Highlights

The workshop explored the issues of quantifying expert judgment and the use of expert judgment in supplementing data, validating models, making programmatic decisions, and licensing nuclear power plants. Examples of its use by the electric utility industry and by other agencies and countries were also discussed.

The keynote speaker[40] was particularly thought provoking. He pointed out the factors in making quality decisions including the appropriate framing of the problem, creating doable alternatives, employing meaningful and reliable information, delineating clear values and trade-offs, using logically correct reasoning, and having a commitment to action. Of particular interest were the possible failure modes for each of these elements; for example, focusing on what is known rather than what is important, or not involving the decision makers in the planning phase of the project. The proper framing of an analysis was cited several times during the workshop as a particularly important issue that must be addressed.

One example of improper framing was the *Calico Hill Risk/Benefit Analysis* (discussed in the Board's *Third Report*), where the DOE needed to supplement the original "value of information approach" with a "multi-attribute utility analysis" because the original analysis failed to take all the relevant factors into

38 *Expert judgment can be defined as an inference or evaluation based on an assessment of data, assumptions, criteria, and models by one or more experts in their field.*

39 *Decision analysis includes a logical decomposition of the problem, the solicitation of expert judgment, means for working out inconsistencies in these judgments, and explicit treatment of uncertainties. Intuitively it can be thought of as "a formalization of common sense for decision problems that are too complex for informal use of common sense" (R. Keeney 1982).*

40 *Professor Ron Howard of Stanford University*

account. Proper consideration of all the relevant factors in the beginning, presumably through increased management involvement, could have obviated the need for a recalibrated analysis.

It was pointed out that reliable data are only meaningful when interpreted through models created from the knowledge of experts. A necessary attribute of a true expert is the recognition of the limits of his or her knowledge. The importance of the *clairvoyance/clarity test* was emphasized. This is an exercise by which experts are trained not to confuse unknown parameters that they are estimating, with ambiguities associated with an unclear definition of these parameters. An example of this is the estimation of maximum earthquakes in earthquake source zones. In past earthquake hazard studies, experts have often arrived at different estimates for the same earthquake source depending upon whether they were considering the *maximum possible earthquake* (no matter how remote the possibility), the *maximum credible earthquake* (which assumes some level of believability), or the *maximum historical earthquake* (which is based upon historical experience).

Presentations at the workshop also indicated that formally elicited expert judgment and the collective judgments of panels of experts have been successfully introduced as evidence in NRC licensing board hearings for nuclear power plants. Therefore it appears that *admissibility* of elicited expert judgment should not be of concern to the DOE in developing its license application for a high-level waste repository. However, the *probative value* of each judgment — in other words, the weight that the licensing board places on the judgment or the extent to which that board believes the judgment to be valid — is another issue. It is not uncommon for licensing boards to admit a particular expert judgment, but to place little or no weight on that judgment in making a licensing decision.

The Board believes that the DOE should work together with the NRC in verifying that formally elicited expert judgment will be admissible in repository licensing hearings. They should also jointly address the definition of guidelines such that the probative value of this judgment is enhanced.

Workshop Steering Committee Recommendations

On April 30, 1993, the workshop steering committee (made up primarily of DOE contractors) issued a technical summary of the meeting and a report, which made recommendations to DOE management on the use of expert judgment. Recommendations include:

1. evaluate alternate decision-analysis techniques to those used by the DOE to date;

2. develop a flexible plan for future use of expert judgment;

3. initiate training in quality decision making and the formal use of expert judgment for both executives and analysts;

4. participate in the NRC's trial elicitation of expert judgment on the topic of climate change;

5. hold a meeting with stakeholders, such as the NRC, the Environmental Protection Agency (EPA), the nuclear utilities, and the state of Nevada, to gain insight into alternative views on the use of expert judgment in decision making; and

6. investigate the use of expert judgment by other government bodies, such as the EPA, in regulatory environments.

The Board believes that these recommendations represent worthwhile objectives for the DOE in its efforts to upgrade and systematize its use of expert judgment. Certainly the development of a flexible plan and the initiation of training can increase overall quality and management involvement. However, there does appear to be a problem in the lack of follow through on certain issues. For example, there was no concerted effort by the DOE to participate, in some form, in the NRC trial elicitation on climate change, which already has been completed.[41] Similarly, as explained to the Board at its July 1993 meeting in Denver, the present (1993) iteration of total systems performance assessment (TSPA) will not include any significant changes in expert judgment input as compared to the TSPA carried out in 1991.

In the Board's view, a major element missing from the Workshop Steering Committee recommendations is the need for expert input from *outside* of the DOE and its contractors. As indicated previously, this issue has been raised in four past Board reports[42] and was discussed by several participants at the workshop. In a response to a specific Board recommendation in the *Second Report*, the DOE stated that:

> *In the past year DOE has employed several outside experts in decision analysis in the course of ongoing studies, to obtain the views of DOE and DOE contractor personnel who are considered to be experts in the areas with high uncertainty. In the future, DOE will continue to seek opportunities to use a diverse group of experts and, where appropriate, increase the use of different outside experts on major issues where peer reviews are warranted.*

The Board believes this response to be inadequate. The issue is not limited to the use of outside experts in decision analysis or on peer review panels, but rather is primarily concerned with the use of outside experts to provide input directly to key analyses such as performance assessment. Outside expert judgment has been used very effectively in both the Waste Isolation Pilot Plant in New Mexico and in the Yucca Mountain performance assessment studies by the Electric Power Research Institute (EPRI). At the July 1993 Board meeting in Denver, the DOE attributed its lack of the use of outside expert judgment (in the current iteration of the TSPA) to a lack of sufficient funds.

The Board is concerned that the DOE apparently views outside expert judgment as a luxury that can only be employed when funding increases. The use of outside experts not only increases the pool of expertise available on any particular issue, it also helps widen the perspective of those involved, no matter how proficient they are. There is a risk that groups of scientists and engineers working on difficult and controversial issues can develop inbred views that need to be challenged by fresh perspectives. Although outside peer review by special committees can help, these committees often do not get involved in detail sufficient to address all critical assumptions. Last but not least, the use of outside expert judgments can make a major contribution to a study's credibility with the scientific community, public officials, and the public itself. Although it may not be true, there is a perception that expert views on issues related to a particular project, supplied only by individuals who derive their livelihood from that particular project, could be biased. Even modest uses of outside expert judgment (not only peer review) in performance assessments would serve to enhance both the quality of the performance assessments and their credibility among those outside of the DOE.

One area where the use of outside expert judgment would serve DOE well in its present program is volcanism. In its *Fourth Report* the Board outlined some of the contentious issues surrounding this topic. There are strong disagreements between DOE contractors and scientists from the U.S. Geological Survey, between DOE contractors and the scientists working for the state of Nevada, and between DOE contractors and scientists at the NRC. The Board recommended a structured probabilistic approach to help discriminate between those differences of opinion that have a significant effect on volcanic hazard assessment and those that do not. External expert judgment including the participation of scientists with different views could greatly enhance the credibility of such a probabilistic study and its results.[43]

From the Board's perspective, it is most important for the DOE to build upon its ongoing experience with expert judgment. Repeated practice, learning from past mistakes or inadequacies and incorporating the lessons learned into ongoing efforts is a most productive means by which the DOE can improve its use of expert judgment.

41 *Center for Nuclear Waste Regulatory Analyses, Expert Elicitation of Future Climate in the Yucca Mountain Vicinity, Iterative Performance Assessment Phase 2.5, August 1993*

42 *The use of outside expert judgment was discussed in the Board's First, Second, Fourth, and Fifth Reports.*

43 *It is our current understanding that the DOE is planning to fund an evaluation of volcanic hazard using outside expert judgment.*

Conclusions

1. The DOE's November 1992 workshop on expert judgment was a successful attempt to bring together practitioners, users, and managers to air their views on the appropriate use of expert judgment.

2. The recommendations of the workshop steering committee are worthwhile objectives. DOE should follow through on these recommendations with the aim of improving both the quality of expert judgment and increasing the involvement of management in planning and implementing those studies that make use of expert judgment.

3. The primary means by which the use of expert judgment will be improved is through repeated practice and learning from past mistakes.

4. DOE has unnecessarily delayed the increased use of expert judgment from sources outside the DOE and its contractors.

Recommendations

1. The DOE should prepare and implement a plan to increase the quality and effectiveness in the use of expert judgment in the high-level waste program. This plan should include:

- establishing guidelines for the use of expert judgment in both programmatic studies and performance assessments;
- increased involvement of management in planning and monitoring the use of expert judgment;
- increased use of *outside* (of the DOE and its contractors) expert judgment; and
- development of an experience base that includes the use of expert judgment in both internal studies and those involving interaction with external groups such as the NRC.

The Board would like to have this plan presented for discussion at a 1994 Board meeting.

Hydrogeology and Geochemistry

A key step in evaluating the performance of a high-level waste repository is establishing the *source term*, that is, the potential rate of release of radionuclides from the engineered barrier system (EBS) to the surrounding near-field geologic environment.[44] This release is the source of radionuclides that could be available to be transported through the near- and far-field geologic barriers and, possibly, to the biosphere.

The EBS includes the waste form, the waste package, any internal buffer or filler materials, and any external engineered barriers that surround the waste packages. The magnitude of the source term depends on the performance of the EBS. The performance of the EBS, in turn, depends on the near-field geologic environment within which the EBS resides. Once waste has been emplaced, the near-field geologic environment could be changed by heat from the waste and by chemical interactions with the EBS materials. This "coupling" of EBS performance with conditions in the near-field geologic environment poses a significant challenge when trying to accurately project the potential source term for a repository.

Source term projections may involve, among other things, estimates of canister corrosion, corrosion of spent fuel cladding materials, oxidation or alteration of the waste form, dissolution of radionuclides, and changes in the geochemical environment of the EBS. Board meetings in April and October 1992 and January 1994 reviewed experimental and modeling efforts to project the source term for a repository, as well as the use of source term models in repository performance assessments. The following sections focus particularly on two areas: (1) radionuclide releases from spent fuel and defense waste glass, and (2) geochemical modeling related to the source term.

44 The near-field geologic environment is a zone, generally considered to be at least a few meters wide, extending outward from the EBS that will be markedly disturbed by mechanical, thermal, and chemical effects.

Application of source term models in performance assessments also is discussed.

Radionuclide Releases from Spent Fuel

Much attention has been focused during the last few years on the release of the radionuclide carbon-14 (^{14}C) from spent nuclear fuel. The release of ^{14}C has been of special concern because it oxidizes to form carbon dioxide gas, which could travel rapidly through the unsaturated rocks of Yucca Mountain to the ground surface. Projected releases of ^{14}C could exceed the allowable release limit of previous regulatory criteria (which are now under review).[45] However, gaseous releases of ^{14}C to the atmosphere would be diluted rapidly in the environment. As a result, projected individual dose rates would be very small.

Carbon-14 in spent fuel is formed primarily when neutrons activate nitrogen impurities present in fuels or structural hardware. The current knowledge of the inventory, the physical distribution, and the chemical forms of ^{14}C is based on a combination of measurements and calculations. Because the concentrations of nitrogen impurities vary among materials and manufacturers, projections of ^{14}C quantities and characteristics are somewhat uncertain. Still, the uncertainties in current inventory estimates are probably smaller than uncertainties in other parameters needed for ^{14}C source term estimates. To develop an improved source term for gaseous release of ^{14}C, more realistic projections of the timing of container failure, as well as determination of the release rates of ^{14}C from the cladding of fuel rods, from fuel hardware, and from the uranium dioxide matrix (UO_2) of spent fuel, would be required. However, because of the small individual dose rates associated with gaseous ^{14}C release, the Board does not believe the DOE should place a high priority on developing an improved gaseous ^{14}C source term unless it becomes clear that future regulatory criteria will significantly restrict such releases.

Development of a source term model for aqueous release of radionuclides requires an understanding of how spent fuel reacts with any water that might enter a breached container to release soluble or colloidal radionuclide species. The Pacific Northwest Laboratory has developed an experimental technique to measure the inventory of radionuclides that reside in the gap between the fuel rod cladding and the spent fuel, as well as along spent fuel grain boundaries.[46] Determining these inventories is important because, when water contacts oxidized spent fuel, there may be relatively rapid releases of the inventories of soluble fission products, such as cesium-135 (^{135}Cs) and iodine-129 (^{129}I), present in the gap and along grain boundaries.

Considerable progress has been made in understanding how rapidly the UO_2 matrix of spent fuel could oxidize and dissolve under the thermal conditions expected at Yucca Mountain. At temperatures up to about 195°C (possibly higher) in the presence of moist subterranean air, the surface of spent fuel UO_2 oxidizes to $UO_{2.4}$[47] without changing its structure or volume. Thus, the fuel rods remain physically intact, and greater than 98 percent of soluble fission products stay trapped within the fuel matrix. Under these conditions the radionuclide release rate is limited by the dissolution rate of the overall fuel matrix. If temperatures were to exceed 350°C, however, $UO_{2.4}$ would further oxidize to U_3O_8 causing expansion of the uranium fuel matrix. This expansion could split open the fuel rod, increasing the surface area of the spent fuel matrix exposed to potential water contact.[48] Oxidation to U_3O_8 also would increase the dissolution rate of the fuel ma-

45 *The U.S. Environmental Protection Agency's regulation 40 CFR Part 191 previously applied to all high-level waste repositories. The Energy Policy Act of 1992 directed the Environmental Protection Agency to develop new standards (separate from 40 CFR Part 191) for a Yucca Mountain repository. Those standards are to be consistent with recommendations to be developed by a panel of the National Academy of Sciences.*

46 *Drs. Robert Einsizer and Walter J. Gray, presentations to the Board on October 14, 1992.*

47 *$UO_{2.4}$ is an empirical formula indicating approximately 2.4 atoms of oxygen for each uranium atom.*

48 *At temperatures above 350°C, creep of zircaloy cladding would increase, further increasing the potential for water to contact the uranium fuel matrix.*

trix, reducing the ability of the matrix to retain radionuclides. Thus, high temperature conditions (exceeding 350°C) are expected to increase the release rates of highly soluble radionuclides, whose releases would be limited by the dissolution rate of the intact spent fuel matrix at lower temperatures.

Experiments have shown that the dissolution rates of $UO_{2.4}$ are essentially the same as for UO_2. This is important for two reasons. First, since the oxidation rate of UO_2 to $UO_{2.4}$ is relatively independent of moisture content, moist-air oxidation of UO_2 to $UO_{2.4}$ below approximately 195°C should not significantly enhance the release of radionuclides. Second, if phases more oxidized than $UO_{2.4}$ can be avoided in a geologic repository, the considerable international data on dissolution of UO_2 from spent fuel can be used to supplement such data collected within the U.S. program.

Additional experiments suggest that the dissolution rates of spent fuels are relatively insensitive to the length of burnup of the fuel.[49] Should this relationship hold up under further testing, then dissolution experiments could be done more easily with unirradiated fuel and still give useful results. At the same time, however, experimental spent fuel dissolution rates have been found to vary by more than a factor of 10^6, depending on the environmental conditions within which the rates are measured. For example, experimental results indicate that the dissolution rate of spent fuel UO_2 is directly proportional to temperature and to the carbonate content of the water. Future dissolution rate studies need to be carefully designed to fully explore the causes of such variations and to permit the reliable prediction of dissolution rates under expected repository conditions.

Radionuclide Releases from Defense Waste Glass

The DOE is conducting a program that involves both testing and modeling the reactions of borosilicate glass with water. The intent of this research is to understand the reaction mechanisms generically so that the source terms for different formulations of vitrified high-level waste can be predicted.[50]

The modeling of high-level waste glass dissolution is being conducted in close cooperation with glass testing. The long-term rate of glass dissolution is a function of temperature, acidity (pH), and solution composition, as well as the amount of surface area of the glass that is exposed to the solution. Model developers believe they have a reasonable mechanistic understanding of how glass dissolves, but more work is needed to quantify critical parts of that understanding.[51]

Experimental studies of glass reactions leading to dissolution or to colloid formation show that the amount of radionuclides released varies substantially as the reaction with water progresses. A moderately rapid initial reaction rate slows greatly with time as silica concentrations increase in the solution surrounding the glass. At longer times, however, formation of secondary phases causes a more rapid final reaction rate to occur. Temperature, relative humidity, and glass composition are important variables influencing reaction rates. Experimental measurements of glass containing actinide elements showed that ^{237}Np goes into true solution, but significant amounts of ^{243}Am and ^{239}Pu are initially suspended as particulates or colloids. Formation of colloids could have significant implications for later transport of the actinide elements through near- and far-field geologic barriers.

49 *Burnup refers to the length of time the spent fuel was "burned up" in the core of the reactor. Usually, spent fuel is removed after a burnup of 3 years.*

50 *The plans for vitrification of defense high-level waste at the DOE's Savannah River and Hanford sites are discussed in the Board's Sixth Report.*

51 *William L. Bourcier, presentation to the Board on October 14, 1992.*

Geochemical Modeling Related to the Source Term

Geochemical changes within the EBS and the surrounding host rock have been modeled using the computer software package EQ3/6,[52] which has been developed and adapted during the past 15 years to fit many needs within the Yucca Mountain project. The software package consists of two interactive codes. The EQ3NR code makes analytical calculations of the chemical form of dissolved components and compares the states of the system or individual reactions to thermodynamic equilibrium. The EQ6 code makes predictive calculations of future equilibrium states, mineral growth and dissolution, reaction paths, and changes in water chemistry. Some 700 pages of updated documentation have been prepared in the past year so that the software might be independently qualified for work on the project. There are many areas in which EQ3/6 could be enhanced to provide better characterization of the source term, as well as the far-field environment.

Effective geochemical modeling requires the use of a critically evaluated, internally consistent, thermodynamic database for the chemical species and solids of importance. The DOE has made a modest effort during the past few years to review the thermodynamic data available for substances likely to form when actinide elements react with anions in J-13 well water.[53] The DOE has identified, at 25°C, those actinide complexes that have been adequately characterized, and those for which estimated values provide sufficient information. Plans for the future include the experimental determination of thermodynamic constants for selected actinide complexes at temperatures of 60°C and 90°C. This effort is hampered by a lack of feedback from performance assessment needed to provide a priority ranking of specific radionuclides.

Performance Assessment

At its April 1992 and January 1994 meetings, the Board reviewed overall system performance assessments for Yucca Mountain, including limited information about the source term models used in those performance assessments. The information presented at the January 1994 meeting included estimates of very large individual dose rates. These large dose rates may be due, at least in part, to the limited amount of ground water available to dilute any releases that might occur. The Board notes the possibility that some form of dose standard may be advocated by the current National Academy of Sciences Panel on Technical Bases for Yucca Mountain Standards.[54] Such a revised standard may lead to stronger emphasis on EBS source term performance. It is evident that several high-level waste repository programs in other countries (e.g., Sweden, Switzerland, Finland, and Japan) are placing strong emphasis on EBS performance. All these nations have initially adopted dose standards to establish long-term safety for their designs for deep geologic disposal of high-level waste. In general, these standards restrict individual doses for times well beyond the 10,000-year regulatory period that has been considered for a U.S. repository. In these nations, engineered barriers play a significant role in limiting projected individual dose rates to very low levels.

The Board is concerned that more research may be needed in the U.S. program to provide good data on the transport of radionuclides through the EBS and into the host rock. The Board also is concerned that the DOE is not making adequate use of performance assessment to guide its on-going EBS research. Today, many research activities seem to reflect the interests and capabilities of individual researchers. Performance assessment could help evaluate and

52 *Wolery, T.J. 1992. "EQ3/6, A Software Package for Geochemical Modeling of Aqueous Systems: Package Overview and Installation Guide (ver. 7)," UCRL-MA-110662, Pt. 1. Lawrence Livermore National Laboratory, Livermore, California.*

53 *Dr. Cynthia Palmer, presentation to the Board on October 14, 1992. However, the chemical composition of the ground water from well J-13, which comes from the saturated zone, is not a particularly good surrogate for the unsaturated zone water that is likely to contact the waste package. There is also a lack of good thermodynamic data for technetium, tin, and selenium species; these important radionuclides are not currently being studied in the program.*

54 *The Energy Policy Act of 1992 called for a review by the National Academy of Sciences of whether a standard based on doses to individuals would be reasonable for protection of the health and safety of the general public.*

focus the contributions of these efforts to overall program goals.

An EBS design that emphasizes diffusive transport of radionuclides through unsaturated engineered barriers might significantly enhance waste isolation because diffusive transport of radionuclides through partially saturated tuff or tuff gravel may be orders of magnitude lower than under saturated conditions. Research into the mass-transport of radionuclides under unsaturated conditions therefore could lead to the development of engineered barriers with improved waste isolation capabilities.

Conclusions

1. Many research programs appear to have originated from a "bottom up" approach, defined by the interests and capabilities of individual researchers. The Board feels that a "top down" approach is also needed to better focus research activities to serve program needs. Iterative performance assessment and associated sensitivity analyses will provide quantitative and technically defensible bases to make decisions regarding EBS design, to direct experimental data collection, and to decide when enough data have been collected in a given area.

2. Reasonable progress is being made on the study of radionuclide releases from spent fuel and high-level waste glass. In certain cases, these data can be supplemented with data obtained from repository programs sponsored by other countries.

3. At present the geochemical code EQ3/6 has limited capability to model radionuclide sorption and to model fully coupled reactive transport. The code could be modified to meet these needs. However, the size and complexity of EQ3/6 presents major difficulties to creating a fully coupled model. Alternatively, the DOE might consider other well-accepted and simpler geochemical codes[55] to model adsorption or to perform scoping calculations. These simpler codes have been used extensively in calculations of coupled solute transport.[56]

4. Not enough emphasis is being placed on determining the mass-transport of radionuclides under partially saturated conditions

Recommendations

1. The DOE should develop a more coherent plan for using total system performance assessment (TSPA) studies and related sensitivity analyses to (a) focus future source term model development and (b) guide data collection both in terms of prioritizing research and establishing when sufficient information has been obtained.

2. The DOE should improve its capability to model radionuclide sorption and to model fully coupled reactive transport. The DOE needs to carefully compare the merits of further development of EQ3/6 versus adoption and further development of simpler codes.

3. The Board recommends that, as a high priority, the DOE begin to collect and document data on mass-transport of radionuclides in near-field materials under partially saturated conditions. These data should then be incorporated into the DOE's source term model.

Environment and Public Health

The DOE's *Site Characterization Plan* is keyed to a regulation, called the siting guidelines,[57] which was published by the DOE in 1984. The siting guidelines

55 *Allison, J. D., D. S. Brown, and K. J. Novo-Gradac. 1990. "MINTEQA2, A geochemical assessment database and test cases for environmental systems: Version 3.0 User's Manual," Report EPA/600/3-91/-21, Athens, Georgia, Envir. Research Laboratory, U.S. Envir. Protection Agency. Parkhurst, D. L., D. C. Thorstenson, and L. N. Plummer, 1982. "PHREEQE— A Computer Program for Geochemical Calculations," U.S. Geol. Survey Water Resources Inv. 80-96, Revised.*

56 *Mangold, D. C. and C. Tsang. 1991. "A summary of subsurface hydrological and hydrochemical models." Reviews of Geophysics, v. 29, no. 1, 51-80.*

57 *U.S. Code of Federal Regulations, Title 10, Part 960.*

contain no criteria for evaluating the potential postclosure (nonradiological) environmental effects of a repository.[58] However, one of the *preclosure* siting guidelines listed criteria for evaluating environmental quality at a potential repository site. When the guidelines were published, the DOE stated:

> *The preclosure guidelines … are … the most important considerations in protecting the quality of the environment and in mitigating socioeconomic impacts, because most of the environmental effects of a repository will occur during its construction and operation.*[59]

When the Siting Guidelines were published, the DOE committed itself to conducting environmental studies during site characterization. The DOE stated:

> *In parallel with site characterization, the DOE will collect additional information about other aspects of the site. This activity, informally called site investigation, will be carried out in order to establish compliance with the guidelines that do not require site characterization (e.g., demographic, socioeconomic, and ecological characteristics) and to comply with the National Environmental Policy Act of 1969.*[60]

The 1982 Nuclear Waste Policy Act declared site-characterization activities to be "preliminary decisionmaking" activities. Thus, neither preparation of an environmental impact statement nor consideration of alternatives under the National Environmental Policy Act is required for site characterization.

The Board's *First Report* noted that there are potentially significant biological risks related to site-characterization activities and to any future construction and operation of a repository. However, site-characterization activities at Yucca Mountain are not different in kind or intensity from ongoing mining, construction, and pumped irrigation activities in southern Nevada. The Board recommended efforts to characterize and understand the desert ecosystem at Yucca Mountain. Such understanding would provide a basis for predicting the potential effects of repository construction and operation as well as the effects of site-characterization activities. In its *Second Report*, the Board repeated its recommendation for a systems approach to predicting environmental impacts and recommended that studies of soil and site reclamation be integrated into studies of the Yucca Mountain ecosystem.

Terrestrial Ecosystem Activities

The DOE currently is conducting a program of environmental monitoring in parallel with site-characterization activities. This program is aimed principally at demonstrating compliance with applicable laws, regulations and DOE orders. The Board's Panel on the Environment & Public Health reviewed environmental monitoring activities at Yucca Mountain in meetings in 1989 and 1990, and during field trips in April 1993 and March 1994. On November 22, 1993 and March 22, 1994, the Panel on the Environment & Public Health met in Las Vegas to review progress in the Yucca Mountain environmental program, with particular emphasis on terrestrial ecosystem activities. The following descriptions of environmental monitoring activities are based on information presented at those meetings and on a review of relevant DOE documents.

The DOE's stated objectives for its current environmental studies at Yucca Mountain are limited to the potential effects of site-characterization activities. The objectives are:

- Demonstration of compliance with applicable laws, regulations and DOE orders.

- Monitoring for potentially significant adverse effects associated with site-characterization activities.

58 *The absence of a siting guideline addressing the postclosure environmental impacts of a repository suggests that the DOE does not consider such impacts to be a relevant criterion for evaluating site suitability.*

59 *See Federal Register, Vol. 49, page 47723, December 6, 1984.*

60 *See Federal Register, Vol. 49, page 47717, December 6, 1984.*

- Avoidance and mitigation of adverse effects.

Currently, projections of the potential effects of repository construction and operation, and of the post-closure effects of a repository, are deliberately omitted. The DOE plans to address those effects later during preparation of an environmental impact statement (EIS) if the site is judged by the DOE to be suitable for a repository. However, some of the information now being acquired is expected to be useful in the future as a baseline description of the Yucca Mountain biota[61] if an EIS is prepared for a Yucca Mountain repository.

The terrestrial ecosystems activities being carried out at Yucca Mountain include biological surveys, reclamation studies, a desert tortoise program, and a site-characterization effects monitoring program. Each of these is described in the following paragraphs.

1. Biological surveys are conducted before, during and after site-characterization activities. Preactivity surveys identify the potential direct effects[62] of site-characterization activities on important species and important biological resources.[63] Measures to reduce or avoid potential effects, such as modifications of proposed activities or relocation of the activity or an important species, are identified and implemented. Preactivity surveys also determine whether there is a need to remove and stockpile topsoil for later use in reclaiming the site. A total of 179 preactivity surveys are reported to have been completed between 1989 and November 1993.

Monitoring surveys are conducted during site-characterization activities primarily to track radio-marked tortoises, to respond to tortoise sightings, and to relocate or otherwise protect any tortoises that may wander into harm's way. Surveys of vegetation cover, density, and production, as well as of soil moisture and soil and air temperatures also are made each year to note changes. Postactivity surveys are conducted to assess whether mitigation and reclamation efforts have been completed successfully.

2. The reclamation program is intended to learn how to return sites disturbed by site-characterization activities to a stable ecological state with form and productivity similar to predisturbance conditions. The principal challenge in reclaiming disturbed sites in the harsh Yucca Mountain desert environment is reestablishing a vegetative cover that approximates the original plant density and species diversity.

In its *Second Report*, the Board noted the need to study methods for reclaiming areas that will be disturbed during site characterization. Field trips to Yucca Mountain allowed the Board to observe, first-hand, the reclamation feasibility studies now under way. Additional information was presented at the November 22, 1993, meeting of the Panel on the Environment & Public Health. Three major areas of investigation are being pursued: natural succession studies of previously disturbed areas, reclamation trials to test the value of soil preparation and seeding and other reclamation methods, and studies of the viability of stockpiled topsoil.

Several areas at Yucca Mountain have been disturbed since site-selection activities began in 1978. The locations, dates, and types of disturbances have been cataloged, and the natural succession of vegetation after those disturbances is now being studied to evaluate allowing nature to take its course.

61 Current studies emphasize the vascular plant and vertebrate animal components of the Yucca Mountain ecosystem.

62 Examples of direct effects are removal of vegetation and topsoil and the destruction of wildlife habitat. Indirect effects include fugitive dust emissions and disruption of wildlife movements by human contact.

63 The DOE's interpretation of important species at Yucca Mountain includes those that are protected by law or regulation (e.g., the desert tortoise), are candidates for such protection (e.g., the chuckwalla), are commercially or recreationally valuable (e.g., game birds) or are indicator species of radionuclides in the environment (some birds and mammals). Species that affect the well-being of other important species, or which are critical to the structure and function of the Yucca Mountain ecosystem, would also be considered important. However, no such species have been identified to date. An example of an important resource for biota is the burrows used by the desert tortoise.

During its April 1993 field trip, the Board observed on-going revegetation trials at previously disturbed areas at and near Yucca Mountain. These studies are testing different seeding methods (broadcast versus drilling), mulch materials, methods for anchoring mulches, soil amendments, irrigation, fencing, and other factors that might significantly affect reestablishment of vegetation in an arid environment. Unusually high precipitation during the 1991-1992 and 1992-1993 winters may have permitted an unusually high success rate in these revegetation trials. Additional trials should be carried out during drier years.

When sites are to be disturbed, topsoil is often removed and stockpiled for later use in reclaiming the site. The DOE is studying topsoil viability as a function of storage time (less than 6 months and longer term) and of storage pile depth. These studies are also evaluating the effectiveness of different plant species in maintaining the viability of stored topsoil.

3. The desert tortoise program is designed to conserve the tortoise population at Yucca Mountain and to ensure compliance with the *Endangered Species Act*.[64] A "biological opinion" from the U.S. Fish and Wildlife Service allows site-characterization activities to proceed at Yucca Mountain provided that the "incidental take" (number of accidental deaths) of tortoises does not exceed 15. Since fiscal year 1990, only one desert tortoise death or injury has been directly attributable to site-characterization activities.

An initial literature review indicated that much remains unknown about the desert tortoise, including its movements, behavior and conditions of survival, especially for small tortoises. Also, Yucca Mountain lies at the extreme northern boundary of the tortoise's range, raising the possibility that tortoises near Yucca Mountain may exhibit behaviors or characteristics somewhat different from tortoises in California, Arizona, or Mexico. Accordingly, the DOE has instituted a program to study the ecology of tortoises at and near Yucca Mountain, coincident with efforts to evaluate and mitigate the impacts of site-characterization activities on the tortoise.

Studies and activities addressing the direct and immediate effects of site characterization on the tortoise include preactivity surveys to identify tortoises potentially threatened by site-characterization activities, radiomarking and monitoring of tortoises in high-impact areas, relocation and displacement of threatened tortoises, roadway monitoring, education of employees to protect the animals, and studies of the effects of ground motion (e.g., associated with tunnel blasting and seismic tests) on tortoise behavior.

Assessment of cumulative and indirect effects is done by monitoring three groups of tortoises: a "high impact" population in the areas of most intense site-characterization activities, an "area wide" population located in the general vicinity of Yucca Mountain, but outside the "high impact" areas, and a control population located well away from site-characterization activities.

Because the raven is a potential predator of desert tortoise hatchlings and tends to increase in numbers near human activities, the DOE is also monitoring raven abundance at Yucca Mountain and a control area and is monitoring for use of site-characterization facilities by ravens.

4. The site-characterization effects monitoring program is considered by the DOE to be its principal effort to monitor the general condition of the terrestrial ecosystem at Yucca Mountain. Its purpose is to monitor the effects of land clearing (removal or covering of vegetation), human disturbance, increased dust deposition, habitat fragmentation, and release of water to the environment. Potential effects could

64 In 1989, the desert tortoise was listed as endangered under the federal Endangered Species Act. It was reclassified as threatened in 1990. Although the population of the tortoise may number from several hundred thousand to a few million, the desert tortoise was listed as a result of sharp declines in population estimates. Possible causes for these declines have been attributed to a respiratory disease, habitat destruction due to development and human recreation, collection of tortoises for pets, and increased predation of hatchlings by ravens. None of those factors are thought to be a significant problem at Yucca Mountain. In February 1994, the U.S. Fish and Wildlife Service designated portions of the southwestern United States as "critical habitat" for the desert tortoise. Yucca Mountain is not part of that critical habitat.

be direct (loss of individuals or of habitat) or indirect (change of habitat quality).

This program is using a "split plot" experimental design, consisting of 24 "treatment" plots located near disturbances (primarily roads) paired with 24 control plots located 200-500 meters away from disturbances.[65] At each "ecological study plot," vegetation cover, density, and annual vascular plant production; soil temperature and moisture at three depths; precipitation; maximum and minimum air temperatures; and soil properties are being monitored.[66] At eight plots,[67] small mammal populations are monitored for abundance, survival rate, recruitment, and species composition. Various locations and sampling methods are used to monitor reptiles, some invertebrates, predators and rabbits. Monitoring is to be carried out before, during and after site characterization.[68] Most of the biotic and abiotic parameters being monitored are highly variable. Natural variability (e.g., in precipitation and vegetative growth) is assumed to affect treatment and control plots equally. Only if treatment and control plots evolve differently with time will there be an indication that site-characterization activities might be affecting parts of the Yucca Mountain ecosystem.

To date, no significant adverse effects of site characterization have been identified. As expected, biotic parameters have proven highly variable, especially because of the change from the drought conditions of the late 1980s to the unusually heavy precipitation of 1992 and 1993. To the extent that summaries of data were presented for review, it appears that treatment and control plots have responded equally to changing environmental conditions.

The DOE is considering revisions to the experimental design for the site-characterization effects monitoring program. The number of study plots would be reduced from 48 to 15-18, with 5-6 of those being "treatment plots" located near disturbances associated with site-characterization activities. Two groups of control plots (5-6 plots each) would be established, one fairly close (200-500 meters) to the treatment plots and the other a few kilometers away.

Expenditures for environmental programs at Yucca Mountain total approximately $11 million per year, with about $3 million of that allocated to the terrestrial ecosystems activities described above.[69] Of this $3 million, preactivity surveys consume about $400,000 per year, reclamation studies $650,000, the desert tortoise program $850,000 and site-characterization monitoring $900,000.[70] Terrestrial ecosystems activities employ about 25 full-time employees, whose efforts are supplemented by about ten part-time summer employees.[71]

Environmental Impact Statement

As already noted by virtue of the 1982 Nuclear Waste Policy Act (NWPA), no environmental impact statement (EIS) is required for site-characterization activities at Yucca Mountain. However, if the site should prove suitable for development of a high-level waste repository, the DOE will need to prepare an EIS to evaluate the environmental effects of such

65 The "treatment" and control plots are equally divided among the four main vegetation associations found at Yucca Mountain.

66 Fugitive dust levels were monitored through fiscal year 1992, but the results were rather erratic. The DOE has decided to terminate dust monitoring at the 48 study plots.

67 One treatment plot and one control plot in each of the four vegetation associations.

68 Since many of the roads at the site were in place and in use prior to initiation of this monitoring program, it is not possible to reconstruct the predisturbance condition of the site. This program may be able to detect large increases in the level of effects that might be associated with future site-characterization activities or with the cumulative effects of multiple activities. Since there are no experimental data on disturbance phenomena and their biological effects, there is no firm basis for predicting or interpreting any such change.

69 The balance supports overhead and infrastructure, radiological and air quality monitoring, archaeological and water resources studies, and hazardous materials control.

70 The remaining $300,000 is used for "biological support," which includes special studies and reports, document reviews, presentations, tours, and permit acquisitions. It also provides support for quality assurance, safety, and facility/equipment acquisition.

71 Wendy Dixon, presentation to the Board on November 22, 1993.

development. The NWPA provides that the EIS must comply with the National Environmental Policy Act, except that the EIS need not consider the need for a repository, alternatives to geologic disposal, or alternative repository sites. The EIS will presumably need to project the environmental effects of the proposed repository and to evaluate the effects of reasonable alternatives. Such alternatives might include various repository designs, waste package materials and thermal loadings. The DOE currently plans to initiate EIS scoping in 1997 and to complete a draft EIS in 1999. A final EIS to accompany a recommendation for development of a repository would be completed in 2001 (DOE 1991).

The potential postclosure ecological effects of a repository have not been addressed other than to conjecture what changes might be expected. At the Board's July 1993 meeting, and again at the November 1993 panel meeting, the DOE provided briefings on the potential effects of repository thermal loading on the surface and subsurface environment above a Yucca Mountain repository. Increased soil temperature profiles, perhaps accompanied by altered soil moisture, were conjectured to be the most likely physical phenomena that would affect the biologically active soil environment. A sufficiently large temperature increase (greater than 2°C) could cause adverse environmental effects including loss of some species and altered interactions among remaining species. The effects of smaller temperature increases were not assumed to be significant, although uncertainties exist about the types and degrees of change that might occur. Many of these uncertainties could be addressed through appropriate experimental studies, but some uncertainties would still remain.

Concerns

The previous discussion indicates that much has been accomplished in the Yucca Mountain environmental program. While recognizing these accomplishments, the Board continues to have two principal concerns about the ongoing monitoring program and a third concern related to eventual preparation of an EIS for a Yucca Mountain repository. These are outlined briefly in the following discussions.

Ecosystem perspective should be defined.

The first concern involves the apparent lack of an ecosystem perspective in the design and execution of ongoing monitoring activities. Current monitoring efforts are driven primarily by the need to demonstrate compliance with applicable laws and regulations. Because those laws and regulations impose a hodge-podge of requirements, monitoring efforts are producing a hodge-podge of data. Evaluating the full suite of monitoring activities from an ecosystems perspective might identify opportunities to produce a more coherent set of data. For example, the role of soil microbes in the ecosystem could be evaluated to determine whether monitoring microbial characteristics and activity would be useful. Also, the environmental studies (especially those involving vegetation) should be integrated with the geologic and hydrologic studies of the U.S. Geological Survey. Certain parameters (especially those related to the desert tortoise) probably need to be monitored regardless of their significance in the larger context of the Yucca Mountain ecosystem. Still, within the constraints imposed by laws and regulations, opportunities should be sought to monitor those parameters that are the most useful indicators of ecosystem health.

Related to this concern is a need for improved analytical and modeling efforts. Significant amounts of data are now being collected that describe various components of the Yucca Mountain ecosystem, but there is a need for improved analyses to synthesize and evaluate those data to detect potential effects of site characterization; to fine-tune the experimental designs and monitoring methods now being used; and to provide the knowledge base for projecting possible longer term environmental effects associated with repository construction, repository operation, and postclosure waste isolation. For example, models of energy or water flows through the Yucca Mountain ecosystem might allow an improved understanding of ecosystem dynamics and identification of the most important species to monitor as indicators of ecosystem health. Also, a simple model of the population dynamics of the desert tortoise could help to suggest which factors significantly affect the longer term population size and health. This type of simple model might be useful to evaluate the significance of the age structure and sex ratio of the permitted "incidental take" of fifteen tortoises in comparison with other natural causes of tortoise mortality. An analysis or model of future site vehicle traffic patterns during repository construction and operations, and of the implications for future accidental deaths of tortoises might also be useful.

Ecological study plot design may not be effective.

The second concern about ongoing activities is the efficacy of the treatment/control plot experimental design being used to monitor for effects of site-characterization activities — particularly the locations of control plots. The distance separating control plots from disturbances is a trade-off between competing factors. In a split plot design, control and treatment plots should be as similar as possible so that non-treatment environmental variables (e.g., precipitation and wind) will influence the plots equally. Thus, the distance between treatment and control plots should be minimized. On the other hand, the separation distance must be great enough so that disturbances associated with site characterization will not significantly affect control plots. The DOE's plan for a revised study design using two sets of control plots (some near the treatment plots and some a substantial distance away) appears promising. As a supplement to the treatment/control plot monitoring, true experiments could be conducted, for example, by quantitatively administering dust to desert plants. Such studies could provide a basis for understanding the effects, if any, of site characterization on vegetation at Yucca Mountain.

Construction and operational effects including postclosure activities need to be considered.

The final and perhaps most important Board concern is the basis for the DOE's lack of concern about the environmental impacts that might occur during repository construction and operation and after repository closure. As already noted, if the Yucca Mountain site is recommended for development as a repository, an EIS must be prepared to accompany that recommendation. The EIS presumably must project the environmental impacts of the proposed activity and of reasonable alternatives, *including alternative repository designs.* Failure to forecast the scientific information needs for the EIS and to plan appropriate studies to produce the needed information could be the Achilles' heel for meeting the tight schedule of the Yucca Mountain project. Multi-year field studies might be needed to produce the information necessary to predict the long-term interactions between a repository and the surface environmental effects. For example, studies may be needed to determine whether repository induced changes in Yucca Mountain vegetation could affect repository performance by altering the amount of precipitation that can percolate to repository depth. Failure to identify the need for any such studies risks a significant, and costly, delay in the project.

The *Site Characterization Plan* of 1988 assumed a repository conceptual design and a surface thermal impact that no longer are supported by proposed design changes and emerging surface thermal and hydrological understandings. The former projection of a maximum increase in surface temperature of 2°C was based on an assumed uniform heat transfer in the geologic overburden through conduction and a very brief above-boiling thermal strategy. Dismissal of any significant ecological effect of a 2°C surface temperature rise included no examination of the ecological significance of the annual rhythms of changes in soil temperature profiles on biota, for example, the mycorrhizal and other soil biota associated with fracture-rooted desert plant species. More important, the assumption of spatially uniform thermal patterns from repository heat transfer being largely a conduction phenomenon now is contrasted with an alternative model of fracture system heat pipes and water vapor heat transfer. Whether these will have surface manifestation over faults and other fracture systems is unknown.

If the prolonged above-boiling concept proves to be the DOE's repository conceptual design of choice, then these departures raise questions for the assumed "no significant effect" that went into dismissing environmental issues from decisions on the repository conceptual design. Although it may be correct that the areal extent of adverse ecological impacts is fully within an allowable impact, the DOE might be far better able to support such an argument if it had two kinds of information not currently funded in the environmental program: first, some examination of the biota associated with surface fault and fracture expressions and, second, experimental studies of the response of fracture associated biota to subsurface heating over several seasons.

It is important to emphasize that the Board is not predicting significant adverse environmental effects from a Yucca Mountain repository. The Board's concern is that the scientific information base must be developed in a timely way to allow a defensible projection of the effects of a proposed repository and of reasonable alternatives. If multi-year studies are needed to produce the data to support such projections, and if plans for those studies are not developed soon, those studies could become the "critical path" that delays progress in the Yucca Mountain project.

Conclusions

1. The DOE has not used an ecosystem approach for designing its environmental studies. Instead, the studies appear to be driven primarily by the need to demonstrate compliance with applicable laws and regulations. As a result, there is no assurance that the ecosystem components now being studied are the most useful indicators of ecosystem health or of the suitability of the site to host a repository. One or more models of the Yucca Mountain ecosystem would be useful to synthesize the data now being generated by Yucca Mountain environmental studies, to prioritize future studies, and to help project the environmental effects of a repository.

2. The effectiveness of the treatment/control plot design has not been demonstrated for the studies monitoring the effects of site characterization. Establishment of additional control plots farther separated from the disturbances associated with site characterization seems appropriate. True experiments would also help to determine whether site characterization is likely to affect the Yucca Mountain environment.

3. The DOE is only in the initial stages of developing a strategy for forecasting the environmental effects of a Yucca Mountain repository and for developing the technical information needed to support such forecasts. Potential environmental effects need to be evaluated not only for their ecological significance, but also to determine whether changes in vegetation (caused by repository heat) could affect repository performance by altering the amount of precipitation that reaches repository depth.

Recommendations

1. The DOE should develop studies of the dynamics of the Yucca Mountain ecosystem. Studies of water, energy, or nutrient transfers within the ecosystem should be considered, as should studies of the effects of repository heat on ecosystem processes. The goal of the studies should be to identify those components of the ecosystem that are most important for ecosystem health and the components that are likely to be the most sensitive to site-characterization activities, to repository construction and operation activities, and to the long-term presence of a repository at the site. The DOE should develop one or more models of the Yucca Mountain ecosystem based on water, energy, or nutrient transfers. This synthesis should come from integrating the environmental data with the geologic and hydrologic USGS data and models. The model(s) should be used to periodically (e.g., yearly) reevaluate and prioritize future environmental studies.

2. The DOE should pursue its plans to revise its ecological study plot design. The revised design should be reviewed by a statistician experienced in this type of monitoring before the new control plots are established. The DOE should consider conducting experiments in which disturbances would be deliberately applied to study plots to provide a basis for understanding the effects of site characterization on the Yucca Mountain environment.

3. The DOE should accelerate its development of a strategy for acquiring the technical information needed to forecast the environmental effects of a Yucca Mountain repository. For purposes of evaluating the possible linkages between environmental effects and repository performance, the strategy should include an assessment of a "worst-case" scenario involving the elimination of all vegetation on Yucca Mountain. The scoping process for development of an environmental impact statement should

be started as soon as practical to identify major programmatic decisions for which a formal evaluation of environmental impacts is required.

Quality Assurance

Quality assurance can be defined as comprising all those planned and systematic actions necessary to provide adequate confidence that the repository and its subsystems or components will perform satisfactorily. The establishment of a QA program by the DOE is a requirement in the NRC's 10 CFR 60, Subpart G. The Board established its Panel on Quality Assurance (QA) in March of 1990. Its initial emphasis was on examining the process by which the DOE was implementing QA requirements. The Board was concerned that the initial implementation could stifle the need to be sensitive to the special requirements for obtaining the rigorous and creative exploratory research necessary for repository development from its researchers.

The DOE management took steps starting in the second half of 1990 to separate administrative or supervisory requirements from their initial QA procedures for site characterization and to improve the communication between the research community and management through the establishment of technical advisory groups. These groups have provided a forum for addressing issues of concern to the researchers with regard to QA implementation and for developing recommendations for improvement to forward to management. DOE management has responded positively to this process. The Board noted this progress and expressed its satisfaction in its *Fourth Report to the U.S. Congress and the U.S. Secretary of Energy.*

In that report, the Board also noted that, at some future time, it wanted to explore the subject of how data, developed independently of the current DOE program, are qualified. This opportunity came at the Board meeting held in April, 1993, in Reno, Nevada, at which the Board was briefed on the processes for qualifying available software and existing data and analyses that have been developed independently of the DOE QA procedures. The Board also continues to follow reports of QA performance by the NRC and will comment on one such issue.

The Qualification of Existing Technical Work

1. Computer software. With respect to software developed outside of the program's QA process, the Board's conclusion is that the qualifying process is vastly improved and has been streamlined during the last two years. ("Software," for this purpose, refers only to the computer code(s) and documentation; it does not refer to the underlying model.) Two years ago the process was very cumbersome. In response, the technical community aired its concerns at the forum provided by the technical advisory group. A small group was formed to revamp the process and to develop more workable requirements for the QA process. Now, the process of validation is basically one of conducting some test cases to see that "it works" for the purpose intended. Then the code, along with the documentation, is turned over to the software configuration management group for the purpose of maintaining the documentation of future modifications to the programs. If the code is considered later for use for some purpose other than the one for which it was originally qualified, the validation process has to be redone for that new application.

The Board was informed at the April meeting that the NRC has agreed to this process. It thus appears that the QA process for qualifying acquired software is now routine and is no longer a significant issue in the conduct of site-characterization work.

2. Existing data and analyses. The Board was also briefed on the process of qualifying existing data — that is, data acquired outside of the program's QA process. This type of data can be either data developed in the DOE program prior to the implementation of its current NRC-approved QA program or to data developed outside of the program altogether, such as material contained in articles published in scholarly journals.

The process for qualifying existing data is quite formal; it is described in an NRC generic technical position document developed for this purpose.[72] The NRC recognizes four methods for qualifying an existing data set, and it prefers the use of some combination of the four over the use of just one alone:

- Peer review; (the peer review that might have taken place when a refereed journal article was accepted for publication is not acceptable because there is generally no documentation of the process or of the qualifications of the referees.)

- Corroboration by other data sets;

- Confirmatory testing (with the testing done under approved program QA procedures);

- Acceptability of the QA procedure used to collect the data in question (even though it was not approved for the program.)

The DOE position on the use and qualification of existing data is that such data would be qualified only if (1) the data set is to be used explicitly to defend a licensing position; and (2) no other data collected under the program's QA procedures support that position. The decision of whether to use a particular existing data set is, thus, part of the process of license application development. It is made in conjunction with the technical investigators, the managers, the regulatory analysts, and representatives from the counsel's office. As DOE indicated, this category of data will be used "judiciously."

The DOE procedure requires the identification of the need for a particular data set and the recommendation of its use by the principal investigator to the technical project officer. A team is then assembled to decide whether or not to go through with the qualification process and use the data. If the answer is "yes," then the decision is made about which of the four methods, or combination thereof, is to be used. So far there has been only one application of this process: the qualification of a data set related to the issue of extreme erosion.

This DOE presentation to the Board and the associated discussions gave the impression that a decision to use and QA qualify an existing data set is not taken lightly, and that one should not expect it to be invoked unless repository license application requires it.

Recent NRC Comments on the DOE's QA Process

The DOE QA program appears to be working well in other areas as surmised from information gathered during two recent meetings. One is the occasion of a briefing by NRC staff to the Board at the October 1993 Board meeting; the other is a November 16, 1993, occasional DOE-NRC meeting on QA issues.

On the first occasion, the NRC described how some of the DOE's internal QA audits have led to the discovery of serious concerns about the management and operating (M&O) contractor. These issues pertain largely to ESF design control and fall broadly into the categories of: (1) inadequate QA procedures and not following procedures and (2) inadequate control of design information. An example of the former is that "there were no implementing line procedures for the process, design, and verification of design changes, and there was no implementing procedure for the identification and maintenance of information to be determined on design drawings." An example of the second is that "the M&O did not have an adequate procedure in place to control the flow of information between disciplines...".

The NRC staff indicated that they had confidence in the DOE's QA audits and shared DOE's concerns about the findings. Following these audits, the NRC itself identified a number of additional findings concerning the M&O's ESF design control. These concerns can best be characterized as the lack of information or evidence of analysis and data to support some of the decisions made in design. As a result, the NRC is not able to determine the basis for some of the specifics in the ESF design or design changes.

On the second occasion, one of the agenda items was recent DOE QA audits. The discussions and the observations by the NRC generally confirmed the

72 U.S. Nuclear Regulatory Commission. 1988. "Qualification of Existing Data for High-Level Nuclear Waste Repositories, " NUREG-1298, February 1988.

Board's earlier impression that the NRC was satisfied with the ability of the DOE's QA audit process to uncover deficiencies related to nuclear waste management.

Conclusions

Given the discussions on QA at the April 1993 Board meeting, the Board is of the impression that the qualifying of software acquired from outside of the DOE program is no longer an issue because the validating process is now apparently straightforward, routine, and acceptable both to the NRC and the researchers. This outcome may bring about greater flexibility in the choice of computational codes available to the site-characterization researchers. The Board is, therefore, pleased by the resolution of this issue.

The Board also concludes that qualifying existing data is unlikely to be an issue for the DOE, but for very different reasons. Here, it appears the DOE has resolved the issue by deciding that the use of existing data is to be kept to a minimum. The rationale for taking this position seems to be a management decision based largely on avoidance of problems during the NRC licensing process, or events subsequent thereto, rather than a strictly traditional scientific approach. The Board appreciates the fact that project management is often forced to make such decisions, but notes that there are elements of risk-cost tradeoffs that may be sensitive to growing budget constraints. That is, funding may not always be available to duplicate existing data sets, and there may be ways of reducing the cost of qualifying such data. Also as license application approaches, there may not be enough time to generate new data.

Between 1991 and April 1993, the Board has not had a session with the DOE dedicated to QA issues. It has not yet reviewed the on-going implementation of an improved QA process by the management and operating contractor. Such a review could be an agenda item for a future meeting of the Board's panel on QA.

Chapter 3
Resolving Difficult Issues — Future Climates

The successful disposal of spent fuel and high-level radioactive waste in a geologic repository demands that those individuals and organizations responsible for siting and construction of the repository address a number of difficult scientific issues. These are typically characterized by great complexity, uncertain processes, and time frames orders of magnitude greater than those previously considered in human endeavors. Resolving these difficult issues requires gathering the appropriate data, increasing scientific understanding, and effective program management. It also requires clear insight into the role the difficult issues play in the overall goal of the program, that is, the safe and efficient disposal of radioactive waste. Such insight is essential in deciding how much effort needs to be expended on a particular issue. Difficult issues often necessitate difficult decisions on when "enough is enough." With this in mind the Board convened a meeting in Reno, Nevada, on April 21-22, 1993, on resolving difficult issues, using infiltration and future climates as the issue. The Board asked the DOE to illustrate how it plans to resolve difficult issues, in this case, the understanding and quantitative prediction of the movement of water in the unsaturated zone, under conditions far in the future when the climate may be quite different from today.

Both scientists and managers were asked to give their viewpoints on the ways data are, and will be, gathered, analyzed, and interpreted to solve this particular problem. Presentations were made by representatives of the DOE, its management and operating team, the U.S. Geological Survey (USGS), the Lawrence Berkeley Laboratory, the National Center for Atmospheric Research, and hydrological consulting firms working for the state of Nevada.

The following sections discuss the issues raised at the meeting and the Board's views on these issues. This discussion also makes use of information gained from the scientific literature and from a meeting of the Working Group on Long-Range Climate Change convened by the Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste (ACNW) on November 18, 1992.

Definition of the Climate-Hydrologic System and Associated Problems

Yucca Mountain, the proposed site for disposal of the nation's spent fuel and high-level radioactive waste, is located in an arid area of the western United States. The present mean annual precipitation at the site is approximately 150 mm per year. If the site is found suitable, plans call for the repository to be located in welded tuff (a formation of hardened and compacted volcanic ash) approximately 300 meters below the earth's surface and some 200 meters above the regional water table. This places the proposed repository in the unsaturated or *vadose* zone.

The advantages of siting a geologic repository in the unsaturated zone in an arid climate are fairly obvious. Water-induced corrosion is the primary means by which waste containers can be breached, and water represents the primary means by which harmful radionuclides present in the waste can be transported to the accessible environment. The United States is unique in the world in its active investigation of a deep unsaturated zone for a geologic repository. Most other countries concerned about the disposal of high-level radioactive waste lack that option and are concentrating their efforts on rocks such as granite, clay, and salt in saturated zones well below the water table.[1]

The unsaturated zone in Yucca Mountain, however, is not problem free and does present the DOE with some difficult challenges. First of all, much is unknown about the flow of water in unsaturated zones. Unsaturated does not mean water-free. Some water is present in the rock pores and fractures, and it can move vertically and horizontally through the rock layers. In particular, water can flow slowly through the pores of the rock matrix and much more rapidly through the larger and more continuous fractures. Difficulties in data collection, characterization, and the modeling of unsaturated zone flow can be formidable. Another challenge is determining the amount of water that could be present in the rock thousands of years into the future. This is heavily influenced by future climate, the main topic of this chapter.

A problem facing an unsaturated zone repository could be that of design of the repository and the waste package. A repository designed to function well in an unsaturated zone, with little or no water present, may not fare as well if the amount of water present increases or, in particular, if the rocks around the repository become saturated. Waste containment and isolation strategies based on the relative absence of water may prove counter-productive if large amounts of water are present. Thus, for example, the DOE's initial plans for waste emplacement (currently being reevaluated) called for placing thin-walled stainless steel waste containers in vertical boreholes, with an air gap between each waste container and the surrounding rock wall. This gap would provide a barrier to prevent any water present in the rock from reaching the container. If the amount of water in the rock were to increase, or the rock became saturated, such a gap could serve as a "bathtub" for the retention of water within which the waste container would remain submerged and subject to corrosion (Winograd 1991).[2]

The flow, or movement, of water in the unsaturated zone can best be understood by defining a system model. The first element in that model is *climate* or "the meteorological conditions including temperature, precipitation, and wind that characteristically prevail in a particular region."[3] In many ways climate is the *forcing function* that supplies water to, and drives the other parts of, the hydrologic system. Climate is influenced by many factors including the presence of mountain ranges, sea circulation and temperature, and the location and size of ice caps.

When precipitation falls on the surface of Yucca Mountain, some water (particularly if there is an intense storm) will flow over the surface of the ground and drain away from the site. Some precipitation will enter the surface rock and soil. This process is called *infiltration* and it is influenced by the amount and timing of precipitation, and other factors that control surface runoff, such as the local topography, vegetation and surface rock and soil properties. *Net infiltration* can be thought of as precipitation minus surface run-off and *evapotranspiration*. Evapotranspiration is the loss of water in vapor form by evaporation from surface rock, soil and water bodies and by transpiration from plants. The zone of evapotranspiration is usually the upper five to ten meters of soil and rock, but its thickness can vary substantially. The movement of water through the unsaturated zone below the zone of evapotranspiration is called *percolation* (flux). It is controlled by the geological and hydrologic properties of the rock in the unsaturated zone, some of which may change as the amount of infiltration changes.[4] The proposed repository horizon is within the zone of percolation,

1 *Based on recent conversations with foreign scientists visiting the Nuclear Waste Technical Review Board's office, a repository for high-level radioactive waste, located in unsaturated crystalline rock is being considered in Russia, and China is thinking about the Gobi Desert as an option for the location of its repository.*

2 *An additional and oft-cited problem associated with the lack of water at an unsaturated zone repository is the release of radionuclides in gaseous form. This issue, and its significance or lack thereof, has been a topic in several of the Board's reports, such as the First Report and the Sixth Report.*

3 *This definition was taken from the American Heritage Dictionary.*

4 *In addition to the shift from matrix flow to fracture flow as water flux increases, E. Kwicklis, at the April 1993 Board meeting described model studies that show the increasing role of larger fractures compared to smaller fractures under this increasing flux. In the*

and the presence of tunnels and heat-producing radioactive waste may have an important effect upon the movement of water in the rock. Eventually, downward moving water in the unsaturated zone reaches the water table and the saturated zone. The process of adding water to the saturated zone is called *recharge*. Water vapor also moves through rock strata and soil along vapor gradients, generally in pathways from wetter and warmer areas to drier and colder ones.

Predictions of the processes in the above system are very problematic. The climate can, of course, change and even if it did not, there is no simple relationship between climate, infiltration, percolation and recharge. Predictions require both models and data. Defining the appropriate conceptual models for climatological processes and all their interactions, or the relationship between matrix and fracture flow are not easy tasks. As discussed below, the influence of our industrial society on climate is not easily accounted for. Computational problems are formidable. Climate models, in particular, can require massive amounts of time on the largest of mainframe computers. The usefulness of such models may be limited by current computational capacity. Data needed as input to these process models vary and may not be of sufficient density (for example, the distribution and nature of fractures) to fully describe the flow regime.

In the past, the Board has discussed problems of flow in the unsaturated zone (see, for example, the *Fourth Report* and the *Sixth Report*). As data are gathered, new information comes to light which can raise new questions and challenge previous assumptions. At the April 1993 Board meeting, for example, a U. S. Geological Survey scientist presented results from the first systematic effort at exploring the deep unsaturated zone at Yucca Mountain (drill hole UZ-16). The fracture density in the welded tuff (Topopah Springs formation) was found to be more than twice as high as previously estimated. Based on previous experience with drill-hole core samples of the rock of Yucca Mountain, many of these fractures are undoubtably filled with mineral matter or are discontinuous and thus not conducive to the fluid flow. In addition water was present in fractures some 12 meters higher than expected based upon previous information as to the position of the water table.

In this report we will concentrate on climate, very much aware of the important and highly complex relationships between the different elements in the system outlined above.

Past Climates

A basic component of the DOE's climatological studies at Yucca Mountain is the description of past climates. The stated aim is to characterize the climates during the past million years with emphasis on the most recent 200,000 years. This characterization is to be inferred primarily through the collection and interpretation of paleontological and geochemical data.[5] Fossils and fossil assemblages, when available and accurately dated, can provide great insight as to the climate during the time that these fossils flourished. *Ostracodes*, for example, are microscopic aquatic crustaceans that are very sensitive to their environment and have been around for hundreds of millions of years. By dating fossil ostracode assemblages at a location in the Las Vegas Valley (about 80 kilometers east of Yucca Mountain) and comparing them to current ostracode assemblages at other locations (and climates), the project scientists infer that 15,000 years ago the average precipitation was 340mm/yr, about three times that of today at the same location.[6]

A particularly powerful technique for characterizing past climates has been the evaluation of fossil packrat middens or den deposits. The middens are com-

unsaturated zone, water paths may not be the same under different climate and flux conditions.

5 *The discussion of these data is based largely on a presentation by J. Stuckless at the April 1993 Board meeting.*

6 *One implication of this comparison is that the climate 15,000 years ago in the Yucca Mountain region is similar to the current climate in north-eastern Nevada (Forester, R. M. and A. J. Smith, "Microfossils as indicators of paleohydrology and paleoclimate," OECD Workshop on Paleohydrological Methods and Their Applications for Radioactive Waste Disposal, Paris, 1992). A similar conclusion, using an entirely different analysis, was reached by M. Mifflin at the April 1993 Board meeting.*

posed primarily of mummified plant fragments, microscopic pollen grains, and fecal pellets encased in crystallized urine. Based primarily on the behavior of modern packrats, the plant fragments are believed to be derived from plants that were growing within 30 to 50 meters of the den. Evaluation of the plant macrofossils and pollen in the middens allows paleoecologists to determine the local and regional vegetation and, therefore, the climate during the periods the middens were in use. Thus, for example, there is packrat midden evidence (National Research Council 1992) that some 50,000 years ago, there were *phreatophytes*, or plants that obtain their water from saturated soils, on the walls of Fortymile Canyon (just northeast of Yucca Mountain) 60 meters above the present canyon floor. If corroborated, as discussed below, this could indicate a water table some 100 meters higher than it is at present.

Geochemical data from rocks at various depths also help determine previous elevations of the water table. These data include strontium isotope ratios in calcite deposits, calcite fluorescence, and mineralogic alteration such as the formation of zeolites. As with the fossil evidence, dating the age of the sample is of prime importance in reconstructing *paleohydrologic* (past hydrologic) and *paleoclimatic* (past climatic) regimes.

Current interpretations (Winograd et al. 1985) of available data indicate that the southern Great Basin, in which Yucca Mountain is located, has been undergoing generally decreasing precipitation and increasing aridity during the past several million years. This decrease is believed to be due primarily to the rise of the Sierra Nevada mountains and Transverse Ranges to the west which serve as barriers to moisture-laden Pacific Ocean storms blowing in from the west. Yucca Mountain and the whole region to the east of the Sierras are said to be in the mountain ranges' *rain shadow*.[7] Superposed on this trend in aridity is the most recent series of global cycles of glaciation and deglaciation that began about two to three million years ago in the northern hemisphere.[8] The last glacial maximum occurred about 18,000 years ago. At that time large ice sheets covered parts of North America and Europe, and sea levels and sea temperatures were lower. The mean annual temperature in southern Nevada may have been 6-7°C cooler than the present, with the Pacific Ocean storms entering North America further south than they currently do. At about this time, and during the ensuing several thousand years, many intermountain basins north of Yucca Mountain were the sites of lakes, both large and small. Similarly, an extensive portion of Death Valley (southwest of Yucca Mountain) was covered by a lake at least 85 meters deep. During the period between 18,000 and 6,000 years ago, in general, temperatures increased, global ice volume decreased, and the seas rose to about their present levels. We are presently in a relatively warm and dry interglacial period, which began some time after 11,000 years ago.[9] It is generally believed that glacial periods last about 90,000 years and interglacial periods last from 10,000 to 20,000 years. Some believe the present interglacial may last for an additional 10,000 years.[10]

Aside from these longer term variations, there are other phenomena that can have a short term effect on the climate; these include volcanic eruptions and El Niño (a complex set of changes in water temperature in the eastern Pacific Ocean). Most recently, evidence from ice cores in Greenland (GRIP 1993) indicates that prior to 8000 years ago there were very rapid changes in climate. The relatively stable climate of the last 8,000 years may be an anomaly when compared to the past several hundred thousand years.

7 *A recent survey of expert opinion (Center for Nuclear Waste Regulatory Analyses, Expert Elicitation of Future Climate in the Yucca Mountain Vicinity, Iterative Performance Assessment Phase 2.5, August 1993) points to the rain shadow as being the dominant factor controlling climate at Yucca Mountain during the next 10,000 years.*

8 *According to the Milankovitch theory, the cycles of repeated glaciation and deglaciation are caused by variations in the Earth's orbital elements, such as the eccentricity of its orbit around the sun and the tilt of its axis of rotation. These variations cause seasonal and geographical fluctuations in the solar radiation reaching the earth.*

9 *Information on past climates is summarized in Chapter 5 of the Site Characterization Plan (DOE 1988).*

10 *I.J. Winograd, presentation at the November 18, 1992, meeting of the ACNW Working Group on Long Range Climate Change.*

It has been inferred that at some time in the recent geologic past, the water table (at least in several places) in the vicinity of Yucca Mountain was 60 to 130 meters higher than at present. This conclusion is based partially upon studies (Levy 1991 and Marshall et al. 1993) of the distributions of zeolitized tuffs, tridymite, and strontium isotopes in drill holes in and around Yucca Mountain. *Zeolites* are hydrous aluminosilicate minerals believed to be formed around or below the water table, *tridymites* are crystal forms of silica probably formed above the water table, and strontium isotope analyses of calcite can indicate the source of the water from which open space fillings and fracture coatings are precipitated. Dates, possibly as recent as 18,000 years before the present, have been associated (Paces et al. 1993) with ground-water discharge deposits in Crater Flat just to the west of Yucca Mountain. These deposits are 80 to 115 meters above the present water table. A modeling study (Czarnecki 1985) provides the support that these rises in the water table were caused by increased precipitation. Using one estimate that precipitation at Yucca Mountain during *pluvial* (high precipitation) times was twice that of today, and a simplified approach that conservatively translates this increase into a fifteen fold increase in recharge, this study concluded that, under these conditions, the water table could rise to 130 meters above its present depth beneath Yucca Mountain.

Paleoclimatic and paleohydrologic data and, therefore, their interpretations have limitations. These can include a lack of spacial resolution, uncertainty in age-dating, and assumed correlations between data and climatic or hydrologic regimes. Thus, for example, the strontium isotope evidence for a higher water table mentioned above, is based on only four samples from one drill hole that show strontium isotope ratios intermediate between those associated with surface ground water and water beneath the water table. This could be interpreted as an anomalous set of measurements or related to localized *perched ground water*, that is, ground water in the unsaturated zone separated, because of local rock properties, from the mass of ground water below the water table. Similarly, the evidence for wet ground derived from pack rat middens high up in Fortymile Canyon has not been corroborated by other nearby middens, and the 18,000 year old date for ground-water discharge in Crater Flat has only been established at one location. Additional data may help remove many of these uncertainties. As discussed below, the questions that have to be asked are, to what extent additional data can resolve those uncertainties, and given the data's potential significance with respect to repository safety, are these additional data necessary.

Nevertheless paleoclimatic and paleohydrologic data provide us with direct evidence of past climate and hydrologic regimes. Although detailed histories, including the exact sequence of different climatic and hydrologic events may sometimes be elusive, these data give us a much firmer grasp of extreme conditions. Such conditions could be the maximum precipitation or the maximum elevation of the water table in a region during a specified period of geologic time. While there is no guarantee that future climatic and hydrologic states will be similar to those in the past, the Board believes that it is appropriate to assume that the paleoclimatic and paleohydrologic data base (to the extent that it is both sufficiently accurate and complete) can serve as an excellent foundation for predicting the range of these future states at Yucca Mountain. As discussed below, however, this assumption falls short when trying to assess the impacts of modern industrial society on future climate.

Climate Models

Fundamentally, the global climate system is driven by heating from incoming short-wave solar radiation and cooling by long-wave infrared radiation into space. This system consists of different components: the atmosphere, the oceans, the cryosphere (ice and snow), the biosphere and the geosphere (rock and soil). The interactions of these components can be very complex. Modeling future climate is an extremely active field of scientific research, spurred on by concern over the impact of present day human activities on future climates and, therefore, future society. Much effort has been expended in developing global *general circulation models* (GCM). A GCM, using known and assumed conceptual models and boundary conditions (such as, input of solar radiation, ice distribution and sea surface temperature), can provide a prediction of climate conditions with a spacial resolution on the order of hundreds to thousands of kilometers. GCM's are generally believed to be successful in simulating the large scale features of present day climate. *Hindcasting*, or the predictive reconstruction of past climates and its comparison with the actual geological record, has had more limited success, the best results being for the past 9,000 year.[11] Attempts to model climate at scales of less than several hundred kilometers present an even greater challenge. These efforts have not always inspired great confidence.

Efforts to model future climate at Yucca Mountain call for the use of a GCM (whose individual grid cells are on the order of 500 kilometers on each side) to provide the boundary conditions, such as, temperature, air pressure, moisture conditions, and wind velocity to a regional model (embedded in the GCM) which covers the United States and parts of Canada, Mexico and the Pacific Ocean. The individual grid cells within the regional model are on the order of 60 kilometers on each side. This grid size is still quite coarse with respect to the proposed Yucca Mountain repository, whose maximum dimension is less than five kilometers, and other methods will be needed to make the results applicable to site-specific processes.[12]

An indispensable part of any investigation involving models is confidence building, particularly for those models used in making long-term predictions. This process has been termed *validation* in the past. However, some experienced modelers recently have objected to that term, because it connotes a once-and-for-all seal of approval for a model.[13] Semantics aside, only the invalidity of a model can be shown absolutely. In the confidence-building process, the model has to be conceptually correct, has to incorporate the right physical, chemical, and biological processes, and be capable of explaining new data. The models are calibrated for conditions at a particular point in time (or space) and then are evaluated on their ability to satisfactorily reproduce conditions that are known for other points in time (or space). With respect to climate models, this evaluation is primarily carried out through the process of hindcasting described above. Even if hindcasting proves to be successful, predictions of future climates may be highly dependent upon still-uncertain conceptual assumptions and boundary conditions.

A particularly challenging problem is calculating the effects of human society on future climate. Much attention as been placed upon global warming caused by an enhanced *greenhouse effect*. The greenhouse effect is a natural effect by which natural greenhouse gases, such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone, in the atmosphere, keep the mean temperature of the earth's surface some 33°C warmer than would be the case if no such gases were present. Natural greenhouse gases impede the radiation emitted by the warm surface of the earth into space. The concern is that modern industrial society's activities, such as the burning of fossil fuels and deforestation will increase the amount of the existing greenhouse gases, and that new, industrial-age, greenhouse gases, such as chloroflourocarbons, are being added to the atmosphere. Current models predict that, if no measures are taken to reduce the emission of greenhouse gases, the global mean temperature could rise 3°C by the end of the next century, with an error band extending from +2°C to +5°C.[14] The climate alteration could also involve changes in the global pattern of precipitation and in sea level. There is still much debate about the extent and impact of increased greenhouse gases in the atmosphere.

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11 *Overpeck, T.J., presentation at the November 18, 1992, meeting of the ACNW Working Group on Long Range Climate Change. See also Kerr, R. 1993.*

12 *Using a finer grid may not be a realistic solution to the problem of spacial resolution. As indicated above, numerical climate models pose a considerable computational challenge. Large amounts of time on the most powerful computers available are already needed. Decreasing the dimensions of the individual grid cells in the regional model from 60 to 30 kilometers, would by itself increase the computational time by a factor of eight (Starley Thompson, personal communication, 1993).*

13 *This material is based largely on a presentation by C.F. Tsang at the April 1993 Board meeting.*

14 *A recent update of these calculations indicates that the projected increase in temperature may be less than originally estimated due to the cooling effect of aerosols (airborne particles) and the depletion of ozone (Houghton et al. 1992).*

Although there were times in the past that the presence of natural greenhouse gases was greater than today, other conditions, such as ice cover and topography, were not necessarily similar, and direct comparisons may not apply. Past analogues of future greenhouse-gas-changed climate have not been found. Thus while paleoclimates can assist in building confidence by hindcasting, they cannot yet be used as predictions of regional climate change due to future increases in greenhouse gases.[15]

There is no doubt that progress is being made in developing better modeling capabilities. This is a rapidly developing field. However, given the complexity of the problem, and our lack of conceptual understanding in a number of areas, it is unclear at what time in the future climate models will be sufficiently mature to provide confident detailed long-term predictions of climate at regional and local scales, such as those associated with the Yucca Mountain site. Climate models could, however, provide valuable insights as to the processes affecting future climate, the likelihood of past climate states occurring in the future and, perhaps, most importantly, the occurrence of climate states such as the enhanced greenhouse effect, which are not reflected in the paleoclimate data base.

A Strategy for Addressing Future-Climate Issues at the Yucca Mountain Site

Given the uncertainties and complexities associated with estimating the future climate at Yucca Mountain, it is incumbent on the DOE and its scientists to have in place a realistic strategy to address this problem. The guiding principle of this strategy should be to frame the prediction of future climates (taking into account existing techniques and potential capabilities) in the context of *program needs* and not theoretical science. This strategy has to recognize that climate prediction is a rapidly developing field and that, for the foreseeable future, a significant measure of uncertainty will accompany such predictions. Many good ideas appear in documents such as the *Site Characterization Plan* (DOE, 1988) and the *Report of Early Site Suitability Evaluation of the Potential Repository Site at Yucca Mountain, Nevada* (DOE 1992), but as of yet no clearly defined integrated strategy has been presented.[16] The *Site Characterization Plan,* in particular, is more like a large menu of possible studies and approaches than a coherent strategy for issue resolution.

To address the problems associated with future climate at Yucca Mountain, the Board believes that the following elements need to be included in the DOE strategy.

1. *An understanding of how climate change can cause the repository system to fail.* The application of complex and uncertain science to the solution of real problems can be made much more effective when the scope of the scientific investigations can be narrowed and focussed in on those issues that are of most concern in the problem at hand. In this case, the problem is protecting the public and the environment from unacceptable levels of risk due to the release of harmful radionuclides, a fundamental question being how future climate can cause the proposed repository to "fail," that is, place severe doubts as to its ability to adequately contain and isolate those radionuclides. Using different climate scenarios (in particular, descriptions of precipitation, temperature and wind), infiltration, percolation and recharge models, and repository designs (in particular thermal loading scenarios), performance assessment-based studies should be undertaken which *drive the repository system to failure.* Proposed failure modes should not be limited to flooding the repository, but should take into account a whole range of effects such as increased percolation, elevated water table, shortened ground-water travel time, decreased sorption of radionuclides, surface flooding, the upward movement of water vapor and the creation of new discharge areas.[17] Out of such analyses

15 Most of the material in this section is based on J.T. Houghton, G.J. Jenkins, and J.J. Ephraums, editors, Climate Change: The IPCC Scientific Assessment. Published for the Intergovernmental Panel on Climate Change, Cambridge University Press, (1990).

16 The Board understands that a study plan is being developed by the DOE which may address part of this concern. An emerging DOE strategy was outlined at the February 1994 technical project review meeting.

would come a list of future climate scenarios, failure modes, and related limiting ground-water performance measures, such as elevation of the water table and percolation flux which could seriously challenge the acceptability of the proposed repository.

2. *Analysis of the relevant geologic past — key to determining future climate effects.* The primary, but not sole, component in determining whether the proposed Yucca Mountain repository is susceptible to failure-inducing climate scenarios should be the analysis of paleoclimatic and paleohydrologic data. This analysis should be based upon data from the Yucca Mountain region covering the most recent cycles of glaciation and deglaciation, that is, the Quaternary period, or the last two to three million years.

3. *The supportive role of climate models.* The numerical modeling of climate can play a supportive, but important, role in overcoming the limitations of the paleoclimate data and in estimating the likelihood of adverse climate states. Thus, for example, if paleoclimatic or paleohydrologic data indicate that past climates were such that their recurrence would have little chance of causing the repository to fail, numerical modeling could be used to gain insight as to whether there is a chance that failure-inducing climate scenarios not reflected in the geologic record, including an enhanced greenhouse effect, could occur during the lifetime of the repository. If paleoclimatic or paleohydrologic data indicate that past climates were such that their reoccurrence would cause the repository to fail, numerical modeling could be used to gain insight as to the likelihood of such climate scenarios.

4. *A panel of experts on climate is needed.* Because paleoclimate data alone may be insufficient in predicting future climates, and it is uncertain as to the extent to which climate models will be able to provide high confidence predictions, it would be highly advisable that the DOE assemble an expert panel, made up of prominent atmospheric scientists, paleoclimate data analysts, hydrologists and specialists from other relevant fields, to help guide the program in the integrated use of data and models.[18] The panel should be primarily made up of experts *external* to the Yucca Mountain program. It has been proposed that a chief scientist be appointed to the Yucca Mountain program. Such a scientist should have a key role in integrating the climate studies and coordinating the expert climate panel.

5. *When is enough enough?* The Department of Energy at some time will have to decide when it has reached the point of diminishing returns with respect to its climate-related studies for the Yucca Mountain site. This decision should be based upon input from its own investigators, the expert climate panel, and interactions with regulatory and oversight groups. The key element in this decision should not be the ability to predict future climate at Yucca Mountain, but rather the ability to determine, with sufficient confidence, whether future climate states will or will not cause the repository to fail. There also should be sufficient information to assist repository designers, if the site is found suitable. Current design efforts need to take into account climate information as it is being developed, to the extent that this information could impact proposed repository and waste package design.

Is This Approach Valid for Other Difficult Issues?

The purpose of the Board's April 1993 meeting was to gain insight into the DOE's method of resolving difficult scientific issues by examining the specific topic of future climates and their impact upon the hydrologic regime. It is appropriate to ask whether the approach recommended by the Board outlined above is applicable to other issues. The answer is yes—with some important caveats.

17 A topic not discussed in this report that needs to be addressed by the DOE is the effect of climate change on human activities (such as population shifts) in the vicinity of Yucca Mountain that could make the site more or less attractive as a location for a high-level waste repository.

18 The need for an advisory panel to assist the DOE in climate modeling was originally proposed in section 8.3.1.5 of the Site Characterization Plan. Starley Thompson of the National Center for Atmospheric Research, reiterated this need in his presentation to the Board at its April 1993 meeting.

The call for a coherent strategy based upon program needs is clearly applicable to the range of problems faced at Yucca Mountain. So is the need to understand how the process or phenomenon under consideration can cause the repository system to fail. This, for example, was the approach recommended by the Board in its *Second Report* with respect to earthquake hazard at Yucca Mountain. Similarly, the criteria for determining when enough is enough is generally applicable. However, the interaction between, and priorities assigned to, data and numerical models is clearly problem specific. Much depends upon the availability, quality and usefulness of data, and the level of confidence that can be placed on numerical models. The need for external expert panels is also problem specific. Although the Board has generally called for the inclusion of more external expert advise in the program (see the section in this report on Risk and Performance Analysis), the need to specifically convene a panel is not applicable to all problems. In many cases, a less formal arrangement exposing the views of project scientists and engineers to outside comments may be sufficient.

Recommendations

1. The DOE needs to develop a strategy for addressing climate-related issues that is based upon their significance to repository performance rather than the ability to predict future climate alone.

2. Future climate states should be estimated primarily through the use of paleoclimatic and paleohydrologic data. Numerical modeling can play a supplementary, but important, role in overcoming the limitations of the paleoclimate data and estimating the likelihood of adverse climate states.

3. An external expert panel made up of atmospheric scientists, paleoclimate data analysts, hydrologists and specialists from other relevant disciplines should be formed to help guide the DOE in the integrated use of data and models. The chief scientist, when appointed, should play a key role in integrating the studies and coordinating the expert panel.

4. The range of future climate states at Yucca Mountain should be an acknowledged input to repository design.