TECHNICAL ADVANCEMENTS AND ISSUES ASSOCIATED WITH THE PERMANENT DISPOSAL OF HIGH-ACTIVITY WASTES

Lessons Learned from Yucca Mountain and Other Programs

June 2011

A Report to Congress
and the Secretary of Energy

UNITED STATES
Nuclear Waste Technical Review Board

U.S. Nuclear Waste Technical Review Board

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U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD 2011

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June 2011

The Honorable John A. Boehner
Speaker of the House
United States House of Representatives
Washington, DC 20515

The Honorable Daniel K. Inouye
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable Steven Chu
Secretary
U.S. Department of Energy
Washington, DC 20585

Dear Speaker Boehner, Senator Inouye, and Secretary Chu:

In accordance with provisions of the 1987 amendments to the Nuclear Waste Policy Act (NWPA), Public Law 100-203, which direct the U.S. Nuclear Waste Technical Review Board to report its findings and recommendations to Congress and the Secretary of Energy at least two times each year, the Board submits this report, *Technical Advancements and Issues Associated with the Permanent Disposal of High-Activity Wastes*. Congress created the Board to perform ongoing independent evaluation of the technical and scientific validity of activities undertaken by the Secretary of Energy related to implementing the NWPA.

The purpose of this report is to extract knowledge while it is still available from the experiences to date of the Yucca Mountain deep geologic repository program and other high-activity waste management programs. The report is not an assessment of the licenseability of a Yucca Mountain repository. If licensing goes forward, the U.S. Nuclear Regulatory Commission will determine whether a license should be granted. But, as President Harry S Truman astutely observed, "…there is nothing new in the world except the history you do not know." In this report, the Board examines from a technical perspective the history of the Yucca Mountain program and some other nuclear waste programs and discusses technical information and insights that may be useful for future U.S. high-activity waste management and disposal efforts.

The Board looks forward to continuing to provide independent technical and scientific information to Congress and the Secretary that can be used to inform the decision-making process.

Sincerely,

{Signed by}

B. John Garrick
Chairman

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TECHNICAL SUMMARY

INTRODUCTION

The U.S. Nuclear Waste Technical Review Board was created by Congress in 1987 to evaluate the technical and scientific validity of U.S. Department of Energy (DOE) work related to implementing the Nuclear Waste Policy Act. The Board's major focus for the last 20 years has been on DOE's efforts to develop a deep geologic repository for high-activity waste† at Yucca Mountain in Nevada. As this report is being written, the Administration has eliminated DOE's Office of Civilian Radioactive Waste Management and is seeking to withdraw the license application it submitted to the U.S. Nuclear Regulatory Commission to construct a repository at Yucca Mountain.

An important part of the Board's mission is advising Congress and the Secretary of Energy on technical issues related to management and disposal of high-activity waste. Therefore, regardless of the outcome of deliberations over Yucca Mountain, the Board believes that it is important to extract knowledge while it is still available from the experience of the Yucca Mountain program and other programs. Such knowledge may be useful for future U.S. high-activity waste management and disposal efforts.

This report is not meant to be an assessment of the licenseability of a Yucca Mountain repository. If licensing goes forward, the Nuclear Regulatory Commission will determine whether a license should be granted. But, as President Harry S Truman astutely observed, "…there is nothing new in the world except the history you do not know." The purpose of this report, then, is to extract from the history of the Yucca Mountain program, and to a lesser degree from other programs, some of the technical "lessons learned" that may apply to future U.S. programs for waste management and waste disposal.

LONG-TERM MANAGEMENT OF HIGH-ACTIVITY WASTE—TECHNICAL CHALLENGES

Perceptions of and opinions on managing high-activity waste vary from it being a problem that is the Achilles' heel of nuclear power without a real solution to being a trivial technical problem that is made complicated by mismanagement, inconsistent policies, or political

† The term "high-activity waste" refers to both high-level radioactive waste and spent nuclear fuel.

decisions. Experience indicates that managing high-activity waste is a problem that is neither unsolvable nor trivial. An international consensus has emerged that burial of high-activity waste in a deep geologic repository is technically feasible and that such an approach can provide adequate protection to humans and the environment.

At least at this time, the only potential alternative to deep geologic disposal of high-activity waste is partitioning the material and transmuting it in reactors or accelerators. Although partitioning and transmutation theoretically could reduce waste volumes, there are many practical problems, the solutions to which are still very much a challenge. Moreover, no amount of partitioning and transmutation can completely eliminate the need for deep geologic disposal. All fuel cycles generate long-lived radioactive wastes that cannot be completely destroyed.

The overarching complication of all high-activity waste-management programs is the long-lived toxicity of the waste, which requires isolating it from biological systems, especially human beings, for many hundreds of thousands of years. Understanding the potential performance of a proposed geologic repository is complex because repository performance depends on (1) the integrity of the engineered barriers, including the waste form and its physical state; (2) dissolution and mobilization mechanisms within the engineered barriers; (3) transport, retardation, and sequestering processes in the natural system; and (4) biological uptake. The waste form and heat generated by the wastes are two critical factors affecting basic understanding of a geologic repository. The waste form greatly affects the chemistry when radionuclides are mobilized, and heat generation introduces uncertainties in the analytical models, particularly at temperatures above boiling.

Three categories of radioactive species dominate design considerations for a geologic repository. The *first category* consists of ^{90}Sr and ^{137}Cs. Although they are not considered a long-term repository health risk because of their relatively short half-lives, they are the dominant contributors to the heat released by spent nuclear fuel during the first hundred years after irradiation. They also are a major part of the radiation source to be considered in handling, storage, and transportation operations before disposal. Decay heat can be a major issue in repository design if there are limits on the size of the repository. The *second category* of radioactive species important for repository design comprises the fission products ^{99}Tc and ^{129}I. These fission products are very long-lived and are in some abundance in the inventory. They are generally soluble and thus able to migrate relatively quickly on release to groundwater. The *third category* is from the actinide group of radioactive species. The important actinides include uranium, plutonium, neptunium, and americium. Many of these species also are long-lived.

The very long half-lives of many of these species present major challenges to demonstrating waste isolation and containment. Because movement by or through water is the dominant mode by which radionuclides can reach the accessible environment, geochemical mobility is a principal concern. Projections have to be made about the solubility limits for each species as well as for which ones will move as colloids. The projections may have to extend far into the future, perhaps as much as one million years.

LESSONS LEARNED FROM THE YUCCA MOUNTAIN PROGRAM

The United States has a variety of waste forms with different chemical and physical properties because of their generation through defense activities, reactor-development work, and electricity production. Specialized deep geologic disposal methods that take advantage of these differences may be reasonable to consider. A possible scenario is using deep geologic repositories that permit retrieval of spent nuclear fuel and boreholes that preclude retrieval of waste forms that offer few or no further recycling advantages, such as vitrified high-level waste.

High-activity wastes in the United States are in a wide variety of forms and in some cases, such as much of the liquid "legacy" waste from the Manhattan Project and the Cold War, are difficult to recover from storage and convert to suitable solid forms for permanent disposal. The waste form determines the burden on the engineered barrier system and the natural system of a geologic disposal facility. Thus, there are three options: (1) develop disposal systems that can accommodate a wide variety of waste forms; (2) process or package the wastes into more-or-less standard forms for disposal; or (3) develop separate repositories for classes of waste forms, e.g., deep boreholes for vitrified waste and a deep geologic repository for spent nuclear fuel. Waste-form characteristics and inventories should be reevaluated, and the issue of the optimal disposal method for each waste form should be assessed. The one-size-fits-all approach used by the Yucca Mountain program may or may not be the best approach. Decisions still are being made on these issues, and a timely decision on geologic disposal siting could have a major effect on the availability of a permanent solution for disposal of high-activity waste.

Considerable methodology and evidence have been developed to indicate the technical feasibility of isolating nuclear waste in an unsaturated zone of the subsurface that involves an oxidizing environment, thus expanding the options for siting a repository. Programs both inside and outside the United States have provided evidence that many geologic options can be attractive candidates for a repository, including intrusive or extrusive igneous rocks (e.g., granite, tuff) and sedimentary rocks (e.g., salt, clay).

Studies at Yucca Mountain advanced scientific understanding of water flow in unsaturated fractured rock in arid regions. On the basis of laboratory, field, and analytical work, scientists developed models accounting for runoff, evaporation, plant transpiration, the effect of capillary forces, and other parameters. Various hypotheses were tested in the models, leading to improved insights on flow in unsaturated rock. Yucca Mountain scientists also coupled heat and fluid-mass transport with provision for geochemical reactions in time and space. That coupling allows modeling on time scales that are appropriate for considering disposal of nuclear waste and sets the stage for future advances in modeling and understanding multiphase transport in geologic media.

The Yucca Mountain program contributed to knowledge of how to use mapping and other studies for locating faults and past volcanic activity in the vicinity of potential disposal locations. The location, timing, and amount of movement of these faults and of periods of volcanism were characterized as part of the hazard analysis. The Yucca Mountain program significantly advanced the state of scientific knowledge in several areas, including its rigorous leading-edge investigations of seismic and igneous hazards. State-of-the-art expert elicitations and probabilistic seismic- and volcanic-hazard analyses led to significantly more-robust fundamental understanding of the phenomena and substantially improved technical bases for risk calculations. A diagnostic science was developed based on using precariously balanced rocks as strong-motion seismoscopes at the Earth's surface to constrain the probability of seismic ground motions.

Yucca Mountain engineers and others investigated many alternatives for controlling the temperatures in the repository. Many of the alternatives were quite novel. The work established that there are many ways to meet thermal goals and constraints from which to select for developing an optimal system. The decision on a repository's temperature limit is one that future repository developers face, and it is a difficult one to make.

Contemporaneously with the Yucca Mountain program, similar advances in understanding geologic disposal in crystalline rock, clay, and salt were being made in other countries. Taken together with the American experience, these activities and the data and understanding from them constitute a formidable knowledge base for pursuing geologic disposal in many media.

Research over the last several decades has led to increasing confidence in the ability to provide engineered barriers that will delay dependence on the waste-isolation capabilities of the natural system for extended periods, possibly hundreds of thousands of years. Such a delay dramatically reduces the radiotoxicity of the waste and simplifies the chemistry of the waste that might enter the natural system, thus enhancing the predictability of the long-term performance of a repository.

Assuming that the environments, including temperatures, to which waste packages would be exposed over time in a repository are known or bounded and that appropriate corrosion data are available, the *general-corrosion* behavior of waste packages over long periods is predictable. More difficult to predict are *localized-corrosion* rates. The ability to control waste package materials and fabrication methods enhances confidence in the analysis and prediction of waste package lifetimes. Analyses indicate that the lifetime of the waste package can be very long, if the waste package also is robust (thick-walled). Because of the long-term predictability of waste packages and the positive experience of programs in crystalline rock in reducing environments and tuff in oxidizing environments, the Board recommends that future repository programs in the United States at least *consider* robust waste packages. This is believed to be an effective way to reduce uncertainty in the overall performance of a repository, regardless of the site chosen.

Because waste package design and performance depend critically on environment, studying the evolution of the waste packages' surface environment is important for any future repository. For example, an issue for the waste packages in the proposed Yucca Mountain repository was the possible existence of elevated temperatures in combination with liquid water in the form of concentrated, multicomponent brines, which are a result of exposure to dust-containing ventilation air from the outside. The Yucca Mountain experience should be valuable for future designers of waste packages, particularly with respect to the requirements for demonstrating long-term performance.

Clay-based buffers, fillers, seals, or plugs are used in many repository concepts, and clay is the geologic medium for some proposed repositories overseas. Because swelling clay may play an important role in any future U.S. repository, future U.S. programs should be aware of, and become involved in, cooperative international research efforts on buffers, backfills, and other uses of swelling clays.

A critical factor in assessing the performance of a geologic repository, and thus the achievement of an efficient design, is quantifying the radionuclide source term entering the natural system. Experience indicates an imbalance in the relative emphasis on research in degradation of the engineered barriers and the emphasis on research in mobilization of the waste.

A key calculation of the performance of any repository is the release rate of radionuclides from the engineered barrier system to the natural system as a function of time: the source term. An overarching lesson learned in the Yucca Mountain program is the difficulty of quantifying the properties important to the mobilization and transport of radionuclides. The modeling and simplifying assumptions for radionuclide mobilization and transport in the engineered barrier system were conservative—possibly resulting in an unrealistic characterization of the source term. There are several areas where more-detailed analysis would have resulted in a more transparent if not a more realistic source term. They include more-accurate characterization of the coprecipitation of radionuclides in thermodynamically stable secondary minerals and more-explicit consideration of the rate of diffusive transport of radionuclides through waste-package-alteration materials to account for the transient retardation of radionuclide migration to the natural environment.

Another area of considerable interest has to do with the possibility of localized reducing conditions in an otherwise oxidizing environment. In particular, the presence of abundant reducing material in the engineered barriers and the ability of corrosion products to limit the access of water and oxygen to the waste are likely to cause substantial lowering of the in-package oxidation-reduction potential. For example, despite strong evidence that the presence of large amounts of iron-based waste-package or invert materials significantly reduces the rate of degradation of uranium dioxide or spent fuel by making the local environment less oxidizing, DOE only partially took the effect of these materials on the environment into account in its license application.

Future consideration of sites involving unsaturated zones will greatly benefit from the Yucca Mountain experience, particularly for modeling the mobilization and transport of radionuclides. The studies and investigations associated with the retardation of radioactive-material transport in the Yucca Mountain performance assessment were a major contribution.

There is strong evidence that many of the Yucca Mountain program deficiencies could have been prevented had the project adopted a total integrated systems approach to performing the necessary science, engineering, and construction activity. A critically important element of such an approach is making the right decisions on transitioning from a science program to an engineering program that involves prototyping first-of-a-kind systems.

Although a total system simulation model that included waste acceptance, storage, handling, transportation, packaging, and emplacement was developed for the Yucca Mountain program, it was not fully embraced by all program elements until late and was terminated too early. Such models are key to a systems approach to design and to ensuring that all the elements of the program are appropriately integrated. Different scenarios should be considered that account for such realities as waste handling and transportation issues, construction delays, operational upsets, failures to meet performance goals, and changes in throughput. *Future programs must take integration of the entire system (including reprocessing and recycling, if undertaken) into account at the outset and must maintain that perspective thereafter.* Analyzing and evaluating a waste-management system as an integrated whole enables one to examine system throughput, identify possible choke points, and recognize where various design and operational elements are incompatible. Understanding this and taking it into account are essential for harmonizing cask design, fleet acquisition, handling, access and egress, line-haul operations, and other activities that must be carried out for the system to perform in a safe, secure, and efficient manner. Treating a highly interdependent system in a piecemeal and segmented fashion almost guarantees that all of its elements will not fit together effectively.

Because the transportation-aging-disposal (TAD) canister concept and the multipurpose-canister concept proposed more than a decade before it offer safety and cost advantages, future programs should consider them carefully. The waste package size that was proposed for Yucca Mountain does not allow for direct disposal of loaded dual-purpose canisters without repackaging the spent fuel. Accommodating dual-purpose canisters at Yucca Mountain would have required a slight increase in the size of the Yucca Mountain waste package, a concept that should be considered seriously for future geologic repositories. The experience with TAD canisters and the fact that dual-purpose canisters currently used by nuclear power plant operators are too large for the Yucca Mountain design in the license application argue strongly for addressing the entire waste-management system as a whole, from at-reactor to final disposal, at the earliest possible stage of any new program. For example, for future repository programs, the implementer should ensure that there is compatibility between waste package sizes and the sizes of canisters used in dry-storage systems. DOE also needs to continue pursuing burnup credit vigorously, because it likely will be needed for disposal of spent fuel in any future repository.

Because site selection, site characterization, and repository engineering are such different projects, consideration should be given at the outset to the appropriate skills, organizational form, and institutional form for each project. The Yucca Mountain program was a mix of science and engineering, with the resulting conflicts of authority and management of the two disciplines. In first-of-a-kind programs that involve new technologies, the transition between science and engineering is sometimes difficult to resolve. Nevertheless, the lesson learned is the importance of establishing the point at which the science part of the program assumes a supporting role to the engineering. In particular, once the project becomes an engineering project, the technical and scientific needs of the project should be driven by what it takes to engineer the project to its performance goals. The failure to accomplish the transition from science to engineering until late contributed to many engineering deficiencies in the Yucca Mountain program.

An additional deficiency was the lack of continuity of management, personnel, and funding. Contractors came and went, and managers cycled in and out, while the amount of money available in the next fiscal year was always in doubt and seldom under the control of the management of the program. The principles of good engineering are well known and include the need for a dedicated organization while maintaining continuity of its personnel, especially of its management and principal engineers and scientists.

Besides management issues, the Yucca Mountain program demonstrated the absence of a strong engineering culture, particularly in the lack of prototyping of many first-of-a-kind systems and equipment and the lack of a maintenance program for subsurface repository operation. Examples of prototypes that would greatly facilitate the design include the waste package; the waste package platform; novel instrumentation; any novel equipment used to emplace, move, or install other equipment items; and the underground assembly of the drip shield. An example of a subsurface maintenance program is controlling preclosure drift degradation to prevent its interference with the efficiency of preclosure operations.

The Yucca Mountain program produced the most comprehensive, internationally peer-reviewed repository performance assessment covering a million-year timeframe. More generally, probabilistic performance assessments can provide a balanced assessment of contributors to risk and therefore should be used throughout the life of a program to guide the selection of a research portfolio.

Although the performance assessment, known as the Total System Performance Assessment (TSPA), had shortcomings, many of the models developed for it were unique, and the performance assessment itself was a major contribution to assessing projects involving very long time periods. Although TSPA contained the elements of a traditional probabilistic risk assessment, it was much more tailored to demonstrating compliance with Nuclear Regulatory Commission regulations as opposed to simply answering the explicit question, "What is the risk?" The main contribution of TSPA was that it provided a benchmark for future studies. The scoping of the assessment for nominal and disruptive events and the treatment of uncertainty were outstanding contributions to the risk sciences. TSPA demonstrated that probabilistic, dynamic modeling of large, complex natural and engineered systems can be performed. A critical output of TSPA was an importance ranking of the radionuclides contributing most to the long-term radiation doses at the accessible boundary of the repository. Such output would be extremely valuable for future consideration of chemical separation of radionuclides to simplify repository designs.

An issue with TSPA, however, was its technical complexity in terms of building confidence in the results. Clearly, a version of TSPA that communicates better with both a technical and a public audience would greatly enhance its interpretation and value. An example of a feature of TSPA that could make it more transparent would be to avoid using probability-weighted doses. Rather, the more traditional approach of calculating the risk of specific doses would be more in keeping with practices in the risk sciences.

Another issue of great importance is how well TSPA represents reality. The inclusion of an uncertainty analysis of parameters and assumptions is critical in this regard. This was a major contribution of TSPA, but questions remained about the degree of reality in the models. The developers of TSPA sought to answer this concern with a performance-margin analysis to evaluate the importance of selected claimed conservatisms. Although this was very helpful in improving the transparency of the analysis, there still were some shortcomings. For example, the analysis would have been much more meaningful if it had addressed the effect on repository performance of taking credit for spent-fuel cladding.

Despite the limitations of TSPA, any future attempt to develop a repository at a location other than Yucca Mountain should embrace the principles of systems analysis by including risk assessments for both site selection and site characterization. Trade-off studies should be performed to help determine the preferred geologic media or repository types for each waste form. Additional trade-off studies should evaluate whether processing the waste form or reengineering the engineered barrier system would be beneficial, depending on the geologic media in which disposal is contemplated.

MOVING FORWARD

The knowledge base for geologic disposal of high-activity waste has greatly increased during the last couple of decades. In particular, the experience gained in the Yucca Mountain program on tuff as a repository medium in an oxidizing environment and the knowledge gained in other programs in other geologic media and reducing environments have established a very strong technical base for moving forward with geologic disposal in the United States. A first step would be ensuring that the current technical experience base from the Yucca Mountain program remains readily available and accessible.

Realizing the full benefit of the advanced state of knowledge also requires renewing international cooperation by forging and maintaining strong bonds with the programs of other countries for waste management and disposal, both directly and through the auspices of the International Atomic Energy Agency and the Nuclear Energy Agency. Implementers of new U.S. repository efforts should increase attention to the advanced repository programs of Finland, France, Germany, Sweden, and Switzerland. New U.S. repository efforts involving site selection should examine the site-selection experience of the advanced programs as well as the activities of other nations currently selecting sites. The diversity of geology being considered worldwide is especially significant to the decision-making of the United States on future programs. The collective Yucca Mountain, Waste Isolation Pilot Plant, and international experiences to date strongly suggest that repositories can be developed in many geologic media. Deciding factors for site selection, therefore, may well be nontechnical.

The Board believes that keeping a focus on a permanent solution is critical regardless of what interim measures for managing high-activity waste are charted. Among the reasons are (1) a permanent solution is needed under all foreseeable circumstances; (2) a permanent solution is critical to building public confidence that there is a way of isolating nuclear waste radioactivity from the biosphere to acceptable levels; (3) undue delay in a permanent solution could make tenuous a concept of waste management dependent on institutional stability; and (4) experience indicates that deploying a permanent solution to isolating high-activity waste could take decades. These reasons are believed to be compelling for a focused effort to implement a permanent solution for disposing of high-activity waste.

CONTENTS

ABBREVIATIONS

ABG	Advisory Bodies to Government
BWR	boiling-water reactor
CSDP	Cask System Development Program
DOE	United States Department of Energy
DOE-NE	DOE Office of Nuclear Energy
EBS	engineered barrier system
FSC	Forum on Stakeholder Confidence
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit mbH
HLW	high-level radioactive waste
IAEA	International Atomic Energy Agency
IGSC	Integration Group for the Safety Case
INL	Idaho National Laboratory
LA	license application
LLNL	Lawrence Livermore National Laboratory
LSN	Licensing Support Network (www.lsnnet.gov)
LTCTF	Long-Term Corrosion Test Facility
LWR	light-water reactor
M&O	management and operating (contractor)
Mg	megagram (1 metric ton or 1 tonne)
MOX	mixed oxide (fuel)
MPC	multipurpose canister
NEA	Nuclear Energy Agency
NEPA	National Environmental Policy Act
NRC	National Research Council
NWTRB	U.S. Nuclear Waste Technical Review Board
OCRWM	DOE Office of Civilian Radioactive Waste Management
ORNL	Oak Ridge National Laboratory
PMA	performance margin analysis
PRA	probabilistic risk assessment
PWR	pressurized-water reactor
SKB	Svensk Kärnbränslehantering AB
SNCNW	Swedish National Council for Nuclear Waste

SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SRS	Savannah River Site
TAD	transport-aging-disposal (canister)
TECDOC	technical document
TMRB	Technical Management Review Board
TSPA	Total System Performance Assessment
URL	Underground Research Laboratory
USGS	United States Geological Survey
WIPP	Waste Isolation Pilot Plant
YM	Yucca Mountain

1. INTRODUCTION

In February 2010, the Administration proposed to eliminate funding for the Yucca Mountain program in fiscal year 2011. Explaining this decision, the Administration stated that it "…has determined that developing a repository at Yucca Mountain is not a workable option and that the Nation needs a better solution for nuclear waste disposal." (OMB 2010: 62). Shortly thereafter, the U.S. Department of Energy (DOE) petitioned the U.S. Nuclear Regulatory Commission's Atomic Safety and Licensing Board to withdraw DOE's application for a license to construct a deep geologic repository for spent nuclear fuel (SNF) and high-level radioactive waste (HLW) at Yucca Mountain. By October 1, 2010, DOE had dismantled its Office of Civilian Radioactive Waste Management (OCRWM) and had merged OCRWM's remaining functions under the Nuclear Waste Policy Act (NWPA) into other parts of DOE. Most employees of OCRWM and its contractors have transferred to other parts of DOE, retired, resigned, accepted employment elsewhere, or become unemployed. In short, the program's corporate memory is diminishing rapidly.

One or more geologic repositories eventually will be needed in the United States. The Board believes that there are technical lessons to be learned from the experience gained during the Yucca Mountain program and other repository programs. The lessons could be valuable if the United States embarks on another effort to develop a deep geologic repository. Moreover, many of the lessons are relevant if the Yucca Mountain program is restarted.[1] Therefore, the Board decided to write this report, the purpose of which is to provide a technical-experience and status report on a permanent solution for managing high-activity waste.[2] The report is based principally on the experience gained from the Yucca Mountain program.

As of May 2011, the Yucca Mountain licensing process continues, although at a minimal level. Many parties have been admitted to the licensing proceedings, including DOE, the Nuclear Regulatory Commission, the State of Nevada, several Nevada counties, the Nuclear Energy Institute, and others. The Board is not a party to the proceedings. An extraordinarily high number of contentions, approximately 300, have been allowed into the proceedings by the independent judges of the Nuclear Regulatory Commission's Atomic Safety and

[1] DOE's petition to withdraw its application has been challenged before the Atomic Safety and Licensing Board and in the Court of Appeals for the District of Columbia Circuit. Congress has not determined what funding, if any, the program would receive for fiscal year 2012.

[2] The term "high-activity waste" refers to SNF, HLW, or both.

Licensing Board Panel. The large majority of the contentions are technical. Besides applying to Yucca Mountain, the outcome of many of those contentions could have generic implications. Thus the Board supported (NWTRB 2009a) DOE's plans to continue with the licensing process despite termination of the program (DOE 2009: 504). In 2010, however, DOE decided to discontinue the license application and eliminate all funding for any aspect of the Yucca Mountain program by October 1, 2010 (DOE 2010: 163).

The Board was created in the 1987 amendments to the NWPA (PL 100-203) to provide ongoing independent expert advice to DOE and Congress on technical issues of nuclear waste management and to build public confidence through peer review of DOE's technical activities in the nuclear waste area (Congress 1987a). The Board's responsibilities are to (1) evaluate the scientific and technical validity of activities undertaken by the Secretary of Energy to implement the NWPA and (2) report the findings, conclusions, and recommendations from its evaluations to Congress, the Secretary, and the public semiannually. This report in many respects summarizes the Board's work in fulfilling those responsibilities over the course of the last 20 years.[3] During that time, the Board has examined the latest technologies applicable to deep geologic disposal, transportation, packaging, and long-term storage of high-activity waste. It has conducted more than 130 public meetings, and it has supplemented its technical analyses with an extensive review of international activities, fact-finding trips to DOE sites and National Laboratories, and workshops on generic topics of nuclear waste management.

This report is organized into four chapters following this introduction. Chapter 2 characterizes the technical issues associated with managing high-activity waste. Chapter 3 discusses lessons learned from the Yucca Mountain program. Chapter 4 describes insights from waste-management programs of other countries and the waste-management research and coordinating activities of the International Atomic Energy Agency and the Nuclear Energy Agency. Chapter 5 presents the Board's overall conclusions on scientific and technical issues for future geologic repository programs.

Appendices A-1, A-2, and A-3 give additional detailed information on the waste-package environment, characterization of a potential repository site, and thermal management, respectively. Appendix A-4 contains views and comments of participants in a public "lessons learned" meeting that the Board held on October 26, 2010, in Dulles, Virginia.

The Board members are listed at the front of this report. Board member disciplines include civil engineering, corrosion science, environmental engineering, geochemistry,

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[3] All of the current Board members joined the Board in mid-2002 or later, which is after the Secretary of Energy's February 14, 2002, recommendation of approval of the Yucca Mountain site to the President. According to Section 114 of the NWPA, that recommendation marked completion of site-characterization activities. Thus, this report emphasizes the licensing and engineering phases of the Yucca Mountain program.

geology, hydrology, materials science and engineering, nuclear engineering, physics, and risk assessment. The average professional service of each member is more than 40 years. Members were nominated by the National Academy of Sciences and appointed by the President on the basis of eminence in their respective fields and established records of distinguished service. Four members have served for more than eight years on the Board; six members have served for more than six years; and one member has served for more than four years. In addition, four Board members had extensive interactions with repository programs before joining the Board. No current Board member served on the Board during the site-characterization phase of the Yucca Mountain program, which ended when the President recommended the site in early 2002 and Congress ratified that decision later that year in a joint resolution (P.L. 107-200 July 23, 2002). Lessons learned during the site-characterization phase are based on Board correspondence, reports, and testimony from that period.

2. THE PROBLEMS OF MANAGING HIGH-ACTIVITY WASTE

Perceptions of and opinions on the long-term management of high-activity waste vary from it being the Achilles' heel of nuclear power without a real solution to it being a trivial technical problem made complicated by mismanagement, inconsistent policies, or political decisions. As discussed in the next three chapters, experience gained over the last three decades from the Yucca Mountain program and other programs indicates that it is neither unsolvable nor trivial.

High-activity waste can take on many chemical and physical forms. The waste form of the U.S. commercial nuclear power industry, by far the greatest current producer of high-activity waste, is spent nuclear fuel (SNF). A small amount of commercial SNF was reprocessed, and the resulting liquid waste was evaporated, mixed with glass-forming materials (borosilicate glass), melted, poured into stainless-steel canisters, cooled to solid form, and sealed, a process known as "vitrification." The waste form of government-owned high-activity waste is much more complicated, primarily because of the diversity of SNF resulting from the nation's nuclear reactor development, materials testing, nuclear research, naval propulsion, and weapons-production programs. The management of DOE-owned waste is complicated not only by the different waste forms but also because the waste at each DOE site varies as a result of the specific processing and storage techniques in use.

2.1. ORIGIN AND DESCRIPTION OF HIGH-ACTIVITY WASTE

In terms of radioactivity, the largest amount of high-activity waste by far is the commercial nuclear power plant SNF associated with the generation of electricity. SNF is being generated in the United States at a rate of approximately 2,000 metric tons of heavy metal (MTHM)[4] per year and now totals about 68,000 MTHM.[5]

A much smaller amount of high-activity waste is that from defense operations, much of which is referred to as "legacy waste." The legacy waste is a product of the nuclear weapons program primarily associated with the war years (1941-1945) and the Cold War years (1947-1990). By far, the majority of this waste is in a liquid or sludge form as a result of

[4] A metric ton of heavy metal (MTHM) refers to metric tons of the elements uranium, plutonium, etc., initially in SNF before its irradiation. In this case, it essentially means metric tons of uranium where a metric ton is a unit of mass equal to 1,000 kilograms (2,205 pounds).

[5] Based on Nuclear Regulatory Commission 2010: 78 adjusted to January 2011.

the waste stream from reprocessing the fuel and is in large underground tanks at Hanford, Washington, and the Savannah River Site (SRS) in South Carolina. A much smaller amount is at Idaho National Laboratory. It was originally in liquid form, but it was treated by heat, and virtually all of it now exists in a solid form, calcine. Cleanup of the Hanford and SRS tanks is in progress, and the intent is that the liquid and sludge wastes eventually will be partitioned into more manageable waste forms with the long-lived high-activity components vitrified for disposal in a deep geologic repository.

The smallest amount of high-activity waste includes all other sources of high-activity waste, such as what comes from research and development activities, research and test reactors, advanced reactor development, and limited chemical processing operations.

Because of the much larger amount of SNF compared to other wastes, it is very likely the waste form offering the greatest opportunity for major advancements in the overall management of high-activity waste. **Table 1** shows the approximate amounts of SNF in the United States. Although recycling or partitioning and transmutation of this waste

Table 1

APPROXIMATE AMOUNTS OF U.S. SPENT NUCLEAR FUEL (ESTIMATED THROUGH 2010)

FUEL TYPE	QUANTITY (MTHM)	LOCATION AND TYPE OF STORAGE	COMMENTS
Commercial	51,000	Nuclear Plant Site, Pool	Stored at 72 plant sites in 33 states
Commercial	14,000	Nuclear Plant Site, Dry	Stored at >50 plant sites
Commercial	700	GE Morris Operation, Pool	May be shipped back to generator
DOE Material Production	2,130	Hanford, Dry	Spent fuel from weapons production reactors
DOE Electric Power	283	Hanford, Dry Idaho National Laboratory, Dry Savannah River Site, Pool	Commercial spent fuel shipped to DOE for examination and development
DOE Experimental Power	42	Idaho National Laboratory, Dry Savannah River Site, Pool	Spent fuel from developmental reactors
DOE Test, Research, and Education	26	Hanford, Dry Idaho National Laboratory, Dry Savannah River Site, Pool	Includes some spent fuel from foreign reactors
DOE Defense Power	25	Idaho National Laboratory, Pool and Dry	Spent naval fuel
TOTAL	**~68,206**	**~96% COMMERCIAL SPENT NUCLEAR FUEL**	

eventually may be done on a large scale, economics, nonproliferation issues, and technical issues do not indicate that deployment soon is likely. Meanwhile, taking a hard look at SNF as the principal waste form in the near term is prudent. So, the questions are just what is SNF in terms of a waste form, and what problems does it present for isolation? Much of the information in this chapter is based on a paper prepared for the National Academy of Engineering (Garrick 2003), including the precursor to Table 1.

Except for very small amounts of SNF from the Fort St. Vrain gas-cooled reactor and early stainless-steel-clad assemblies from light-water reactors (LWRs), U.S. commercial SNF is all bundles (assemblies) of zircaloy tubes filled with uranium dioxide (UO_2) pellets enriched in ^{235}U before irradiation in the reactor, pressurized with helium, and closed with welded zircaloy end plugs. For a pressurized-water reactor (PWR), the tubes have outside diameters of approximately 0.4 inch and an overall length of approximately 12 feet. Some 200-plus tubes make up an assembly, and nearly 200 assemblies constitute the reactor core in a large PWR. The dimensions and fuel enrichments are different for boiling-water reactors (BWRs), but the materials and neutronics are similar, resulting in essentially the same requirements for SNF management. **Figure 1** shows a typical 8.5 in. x 8.5 in. x 12 ft. PWR fuel assembly without its end nozzles (DOE 2010).

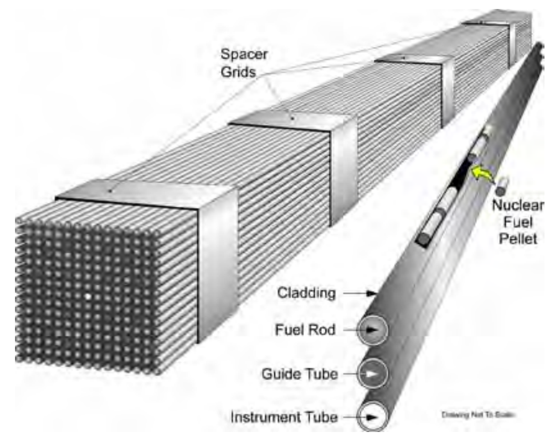

Figure 1: PWR Fuel Assembly

SNF from LWRs contains ^{235}U and ^{238}U; intermediate-lived fission products, such as ^{90}Sr and ^{137}Cs; long-lived fission products, such as ^{99}Tc and ^{129}I; and relatively long-lived transuranic isotopes (i.e., isotopes with atomic numbers higher than that of uranium: 92), such as ^{239}Pu and ^{243}Am. The extent to which the fuel is irradiated (burned up) in the reactor determines the amount of radioactive species created. The units of burnup usually are taken to be the amount of thermal energy produced per initial unit weight of the fuel (gigawatt days per metric ton of heavy metal [GWd /MTHM]). Two burnups frequently are used in the calculations of waste inventories—standard historical burnup and extended burnup. For PWRs, the two burnups are 33 and 60 GWd /MTHM, and for BWRs, the corresponding numbers are 27 and 50 (ORNL 1992). The average burnup of SNF discharged from U.S. commercial reactors in 2001 was approximately 40 GWd /MTHM (DOE 2002). The trend in the nuclear power industry is toward progressively higher burnups, with some assemblies now attaining burnups of 60 GWd /MTHM (Gauld et al. 2011).

There are four sources of radioactivity in SNF—actinides,[6] fission products, spontaneous fission, and materials made radioactive by neutron activation. In LWRs, the UO_2 pellets

[6] Actinides are elements having an atomic number from 89 to 103, inclusive, and are all radioactive.

start out containing only ^{235}U and ^{238}U. After a significant runtime at power, neutron-gamma reactions and subsequent decays will produce 51 actinides. The fissioning of uranium results in 200 to 300 fission products, which dominate the short-term decay heat of SNF.[7] The third source of SNF radioactivity consists of selected actinides that fission spontaneously; that is, they do not need an outside source of energy, such as an impacting neutron, to fission. The fourth source of radioactivity is neutron activation products due to the absorption of neutrons by cladding and other structures inside the reactor.

Thus, when nuclear fuel has completed its multiyear sojourn in a reactor, there are dozens of actinides and hundreds of fission products, most of which are radioactive, that were not part of the fuel originally. In addition, there are some activation products in the structural material, cladding, and fuel matrix. Fortunately, most radionuclides become unimportant for disposal because of their minor quantities, short half-lives, or minor biological consequences. Basically, three categories of radioactive species dominate considerations for geologic repository design. The first consists of intermediate-lived radionuclides, especially ^{90}Sr and ^{137}Cs. Although they are not considered a postclosure repository health risk because of their relatively short half-lives (28.8 years and 30.1 years, respectively), they are the dominant contributors to the heat released by spent fuel during the first hundred years after irradiation. They also are a major part of the radiation source to be considered in handling, storage, and transportation operations before disposal. Decay-heat load can be a major issue in repository design if there are limits on the size of the repository.

The second category of important radioactive species for repository design comprises certain long-lived fission products, such as ^{14}C, ^{36}Cl, ^{79}Se, ^{99}Tc, ^{126}Sn, and ^{129}I. These radionuclides have half-lives of thousands of years or more and are in some abundance in the inventory. In general, they have significant solubility under many circumstances and tend not to be greatly retarded by geochemical effects and thus able to migrate relatively quickly on release to groundwater.

The third category is from the actinide group of radioactive species. Although these isotopes are not very soluble and tend to be significantly retarded by geochemical effects during migration (^{237}Np can be an exception), they have very long half-lives and, as a class, are significantly more radiotoxic than fission and activation products.

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[7] For a spent PWR fuel assembly with an initial enrichment of 3.72% U-235 and a burnup of 40 GWd/MTHM, the heat load decreases from 10,600 watts per MTHM 1 year after discharge to 16 watts per MTHM in 10,000 years. The values for a BWR spent fuel assembly (3.21% initial enrichment and 35 GWd/MTHM) are 9,200 and 15, respectively. Source: Program RADDB (DOE 1987).

2.2. PROPERTIES OF THE WASTE THAT MAKE IT DIFFICULT TO MANAGE

The goal of all high-activity waste-management programs is to isolate the radionuclides from biological systems, especially human beings. That sounds pretty straightforward, but there are complications. Two complications are that the isolation of some waste forms has to be for hundreds of thousands of years and that some radionuclides exist in several phases (gas, liquid, or solid) and have various pathways (ingestion, inhalation, external radiation) for spreading their radiotoxicity. The very long half-lives present major challenges to demonstrating that the waste is not released in unacceptable quantities. Another complication is that the waste may contain 200 to 300 different radioactive species, all of which have different chemical properties, physical properties, or half-lives. In general, the risk posed by a radioactive species depends on its half-life, geochemical mobility, and radiotoxicity.

The good news is that some of these properties work in favor of isolation. Most radionuclides become unimportant quickly because of minor quantities, short half-lives, and minor biological consequences. Thus, although freshly discharged fuel from a nuclear reactor may have some 300 radioactive species that were not in the fuel when it was loaded into the reactor, by the time it is put in isolation, such as in a geologic repository, only a small fraction of the radioactive species represents a challenge to complete containment and isolation. Even that small fraction dwindles to no more than a couple of dozen long-lived radionuclides in several thousand years. Because isolating those radionuclides from the environment is the challenge, they are the focus of this discussion.

Geochemical mobility is a principal issue of geologic disposal. For example, if all of the radionuclides were insoluble, there would be little problem, because the primary transporter of radionuclides in a geologic repository is water. Insoluble species would not be transported in flowing water through the geologic medium, and containment would be achieved, barring something like transport in colloidal form (i.e., transport as a suspension of fine, dispersed particles that do not settle out) or an igneous or other cataclysmic event. However, no species is truly insoluble; virtually all species are soluble in any molecular form, and the maximum aqueous concentration attainable for a given solid is called the "solubility limit." Solubility limits for some species can be high, such as for nitrates, and for the same species be low when in an oxide or hydrated oxide form. Plutonium is an example. Some plutonium compounds have relatively low solubility values—oxides and hydrated oxides are examples. Assuming that the radionuclides in waste forms that have been disposed of in a geologic repository are completely available, the rate of radionuclide mobilization at steady state is the product of the groundwater-flow rate through the waste forms and solubility.

Various processes affect the geochemical mobility of radionuclides. During groundwater flow in a rock matrix or fractures, transport rates for reactive solutes often are slower than the average groundwater-flow rate. This is because of several active phenomena, including diffusion of solutes into stagnant pore spaces, sorption onto fixed mineral surfaces or slow-moving colloids, and chemical processes, such as precipitation and replacement reactions with existing rock minerals. On the other hand, other processes could enhance radionuclide transport (e.g., low-solubility radionuclides, such as plutonium, that attach to mobile colloids). Many of these phenomena are difficult to quantify and depend on the variety of rock types through which groundwater flows and the chemical compositions of the groundwater.

A few radionuclides—for example the fission products ^{99}Tc and ^{129}I—have three properties that makes their isolation difficult: very long half-lives, considerable inventory in the waste, and high solubility limits under geologic conditions.[8] The result is that these two radionuclides are for the most part able to migrate unimpeded in groundwater flow, assuming that no significant retardation processes operate.

Actinides also present isolation difficulties. The important actinides from the standpoint of nuclear waste management are uranium, plutonium, neptunium, and americium. Actinides and their decay products account for much of the radiotoxicity of nuclear waste after the first 500 years of disposal. See **Figure 2** (ORNL 1995; used with permission). Although plutonium species generally exhibit relatively low solubilities in groundwater and neptunium is sparingly soluble, isotopes of plutonium and neptunium nevertheless represent a major part of the risk after several hundred years for oxidizing media. Actinides are responsible for the longer-term heat generation in the repository—particularly ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Am. ^{237}Np is an important daughter product of ^{241}Am.[9]

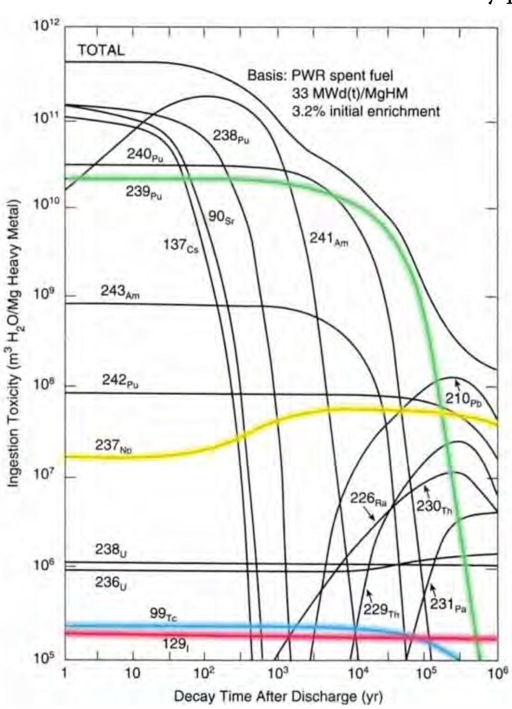

Figure 2. Toxicity from Ingestion as a Function of Decay Time for a Number of Nuclides in Spent LWR Fuel[9]

Although Figure 2 is useful for understanding relative risks of various radioisotopes in a generic sense, it is not repository specific because it does not take solubility limits or retardation (e.g., by adsorption) into account. The performance assessment results of the Yucca Mountain repository program illustrate how actinides and the fission products ^{99}Tc and ^{129}I can affect long-term risk (DOE 2009). At 10,000 years, the principal contributors to the risk are ^{99}Tc, ^{14}C, ^{239}Pu, and ^{129}I. At 1,000,000

[8] The solubility of ^{99}Tc is low under strongly reducing conditions.

[9] Note that the curve marked ^{226}Ra and ^{230}Th represents the sum of the ingestion toxicities of these two radioisotopes.

years, the risk is dominated by ^{226}Ra, ^{242}Pu, ^{237}Np, and ^{129}I. Although these radionuclides were calculated to be the principal contributors to the radiation dose, the implication is not that the calculated radiation doses were high; they were not. In fact, the calculated dose levels were extremely low and were well below the regulatory standard.

Finally, on a more general level of why managing high-activity waste is such a challenge, especially in the United States, considering the waste inventory is important. An often overlooked technical issue facing the United States but not most other countries is the so-called legacy waste, which the United States has in much greater quantity and diversity than do most other countries with nuclear programs. U.S. legacy wastes are in a wide variety of forms and in some cases, such as much of the liquid wastes, are difficult to recover from storage and convert to suitable solid forms for permanent disposal.

The characteristics and integrity of the waste form determine the burden on the balance of the engineered barrier system and on the natural system to contain the waste or to hold it in place until it essentially has decayed to acceptable radiation levels. With its wide variety of waste forms, the United States needs to seek a single disposal system that can accommodate them, process or package (both of which may be extensive and expensive) the wastes into more or less standard forms for disposal, or develop separate repositories for classes of waste forms, e.g., deep boreholes for vitrified waste and a deep geologic repository for spent fuel. Waste-form characteristics and inventories should be reevaluated, and the issue of the appropriate disposal method for each waste form should be addressed. The one-size-fits-all approach used by the Yucca Mountain program may or may not be the best approach. Termination of the Yucca Mountain program means that previous decisions on multiple repositories, waste processing and packaging, and repositories dedicated to classes of wastes will have to be made anew.

2.3. PERMANENT DISPOSAL OF HIGH-ACTIVITY WASTE

Only two alternatives exist for the permanent disposal of high-activity waste: isolation and waste destruction. A third alternative, dilution, is not considered acceptable for high-activity wastes. Destruction alone is not a total solution, because not all the radionuclides can be destroyed. Preparation of the waste for destruction requires extensive processing to separate (partition) selected radionuclides from spent fuel and fabricate them into new fuel or targets for destruction. This then is followed with the actual destruction process (transmutation), either in dual-purpose nuclear reactors (power producers and waste burners) or in special-purpose accelerators. All of these operations, the separation plants, and the special-purpose reactors and accelerators generate their own waste streams. Reprocessing spent fuel, a much discussed form of partitioning, is being reexamined for recovering unused uranium and plutonium for their energy value as well as for reducing the radiotoxicity and volume of waste requiring isolation.

As discussed later, partitioning, including recycling of SNF, and transmutation are being challenged on their technical and economic practicality. Although many technical and economic obstacles to the large-scale use of partitioning and transmutation in high-activity waste management remain, the option of isolating high-activity waste in deep geologic repositories either in vitrified form or as SNF appears close to being achieved. In fact, deep geologic disposal has gained international consensus as the preferred option for managing high-activity waste. Interest in geologic disposal has existed for many decades. For example, the National Academy of Sciences, in one of the first reports on radioactive waste, concluded that geologic disposal of solidified high-activity wastes is feasible and recommended investigating disposal in salt formations (NRC 1957). In addition to salt, other geologic media, including clay, granite, basalt, and tuff, have been investigated as candidate environments for isolating high-activity waste. In addition, engineered barriers have come into focus as being an important part of the isolation strategy because they can provide long delays before radionuclides enter the natural system.

2.4. ISOLATION

The goal of geologic disposal of high-activity radioactive waste is to protect public health and safety and the environment by isolating the waste. A key issue in the performance of a geologic repository is estimating the time and rates of release of the dose-contributing radionuclides from the emplaced engineered barrier system (EBS) to the natural system of the repository. This usually is referred to as the "source term." In general, the longer the waste remains in the EBS, the lower hazard any waste that eventually escapes will present. A well-designed EBS should delay mobilization of the waste and release radionuclides over an extended period.

Analyzing the performance of a geologic repository involves quantifying the source term and assessing how well the natural system isolates the radionuclides delivered to it by the source term. The extraordinarily long time scale, a million years for Yucca Mountain and some other countries (NWTRB 2009b: 9), makes the problem daunting and uniquely challenging.

As further described in chapter 4, experience to date clearly shows major differences in the approach to engineered barriers because they are affected by differences in isolation strategies. For example, France and Germany are investigating clay and salt sites, respectively, and plan on using minimal barriers in addition to the natural system. On the other hand, the proposed repositories of Sweden (granite), Finland (crystalline rock[10]),

[10] Although both the proposed Finnish and Swedish repositories would be located approximately 400-600 m deep in the crystalline bedrock of the Baltic Shield, the geologic media of the two repositories are not identical. The nature of the Swedish repository rock is granitic; the Finnish repository rock is a mixture of granitoids, gneisses, and migmatites.

and the United States (tuff) all depend on the geology providing appropriate environments for their respective robust EBSs in addition to the protection provided by the natural system. The United States, which once seemed well ahead of the repository programs of other countries, is now behind at least Finland, France, and Sweden in terms of projected repository opening dates. However, the United States has an abundance of various geologic media and may well learn from the repository-development experiences of other countries as well as its own experience with Yucca Mountain and the Waste Isolation Pilot Plant (WIPP), a deep geologic repository for transuranic wastes located in salt beds in southeastern New Mexico.

Transport by flow or diffusion in groundwater is the principal pathway by which radionuclides are expected to move from the engineered barriers into the natural system. Some radionuclides may become dissolved in the water or be transported as colloids or attached to colloids. Dispersal and transport pathways other than groundwater also must be considered to quantify the risk associated with a proposed high-activity waste repository. The risks include diffusion of radionuclides as a gas, entrainment of radionuclides in a volcanic eruption, and human intrusion. Yucca Mountain studies indicate that ambient groundwater flow generally represents the most significant pathway for radionuclide release.

Assessing the performance of engineered barriers in a Yucca Mountain repository turned out to be more of a challenge than expected. Much of the challenge was describing the environment of the engineered barriers quantitatively, particularly during the thermal pulse, defined as the period when the surface of the waste package is at or above the boiling point of water. The duration of this period for any particular waste package in the repository design proposed for Yucca Mountain by DOE varied from a few tens of years to as much as a thousand years, depending on the location of the waste package in the repository; the amount, burnup, and age of the waste in the waste package; and other variables. Describing the environment quantitatively requires determining the range of values of the chemical and physical attributes in the immediate surroundings of the engineered barriers, including temperature, water composition, humidity, redox potential, pH, etc. The values are a function of time and location.

There are many cost, performance, and uncertainty trade-offs in the design of engineered barriers. For example, exotic materials such as nickel alloys show great promise in resisting degradation but have an experience base of only several decades and are expensive. Iron has an experience base of many centuries and is low in cost but degrades more rapidly. In addition, there are the very practical problems of constructing underground in confined spaces and emplacing waste remotely in a high-radiation and decay-heat environment.

Heat generation as a result of radioactive decay can complicate fundamental understanding of the performance of a geologic repository because the analytical models used to calculate performance of natural and engineered barriers may not be as reliable for temperatures above boiling as for lower temperatures. There are ways of dealing with the decay-heat or thermal-load problem, however. One way would be to do more research on analytical methods better suited to systems involving chemical, mechanical, thermal, and geochemical coupled processes at above-boiling temperatures. Other approaches would be to use engineering or operational adjustments, e.g., improve heat transfer in the repository or store the waste until a time that the heat no longer is sufficient to cause water to boil. Of course, the heat load often becomes a problem only because of spatial limits on the repository. That is, the problem of excessive heat loads can be reduced simply by using more real estate. Finally, the heat loads can *in theory* be reduced by separating the heat-generating radionuclides from the waste and destroying them through successive neutron reactions.

Human intrusion, deliberate or as a result of drilling operations that inadvertently penetrate the repository, needs to be part of the risk assessment of a proposed geologic repository. Human intrusion is important because it represents a scenario for bypassing both the engineered barriers and the natural system. To date, modeling human intrusion has been considered more of a "stylized" stand-alone analysis rather than an attempt to quantify the actual risk of such a scenario. The performance assessments done for Yucca Mountain have not identified human intrusion as a significant contributor to the risk of a geologic repository. The reason is that the consequences tend to be localized, with very little material reaching the accessible environment. Nevertheless, it is an event that must be considered.

In summary, fundamental understanding of the performance of a proposed geologic repository is a complex issue dependent on (1) the integrity of the engineered barriers, including the waste form and its physical state; (2) dissolution and mobilization mechanisms within the engineered barriers; (3) transport, retardation, and sequestering processes in the natural system; and (4) biological uptake. A fundamental understanding of the waste form is critical not only with respect to its physical and chemical state in a geologic environment but also in knowing how to complement its behavior with protective barriers, including backfills to create favorable geochemical conditions for maximizing containment of the waste.

2.5. PARTITIONING AND TRANSMUTATION

Partitioning is the process of separating long-lived and high-activity radionuclides from the waste to become targets for nuclear reactions, and transmutation is the process of bombarding the selected radionuclides with neutrons to create either stable nuclides or radionuclides with much shorter half-lives. If the species are fissionable in the spectrum of the neutron energies involved, then the reaction products may be fission products, most of which have shorter half-lives than the target species. The devices providing the neutrons are nuclear reactors of various neutron-energy spectrums or specialized accelerators. Both thermal and fast reactors (low-energy and high-energy neutron spectrums, respectively) can be transmuters, although fast reactors offer more flexibility because of their ability to fission the actinides directly.

Partitioning and transmutation are considered potential means of reducing the burden on a geologic disposal repository by reducing the volume of the waste to be disposed of, the heat-generating capacity of the waste, or the time needed until the radiotoxicity of the waste has declined to a low-enough level. For example, because plutonium and minor[11] actinides are mainly responsible for the long-term radiotoxicity and heat generation in a repository, removal of these nuclides from the waste (partitioning) and then fissioning them (transmutation) could result in the remaining waste losing much of its otherwise dominating long-term radiotoxicity and heat-generation capability. The fission products ^{99}Tc and ^{129}I have very long half-lives. With the right neutron spectrum, ^{99}Tc can become stable ^{100}Ru. Similarly, ^{129}I can be transmuted to stable ^{130}Xe. Because plutonium, uranium, neptunium, americium, curium, their decay products, iodine, and technetium are the cause of most of the mid-term and long-term risk of the proposed Yucca Mountain repository, their elimination could make designing a repository much simpler.

So, why not go full speed ahead on an aggressive partitioning and transmutation program, especially because such destruction methods can be applied to widely different fuel-cycle strategies? The answer is that in time that may happen, but probably not unless and until fast reactors become more economic and reliable, and even then, only if nuclear power becomes a major source of energy over other alternatives under development. Although partitioning and transmutation are theoretically possible, there are many practical problems, the solutions to which are still very much a challenge. Also important is that no amount of partitioning and transmutation eliminates the need for deep geologic disposal, because all fuel cycles generate long-lived radioactive wastes that cannot be practically destroyed.

The reasons for not being able to deploy waste-destruction schemes in the near future are many. One overarching issue is developing enough facilities to make a significant difference. Quoting from a National Research Council study (NRC 1996), "…to have a significant benefit for waste disposal, an entire S&T (separation and transmutation) system consisting of many facilities would have to operate in a highly integrated manner from several decades to hundreds of years. The deployment of an S&T system that is extensive enough to have a significant effect on the disposition of the accumulated LWR spent fuel would require many tens to hundreds of billions of dollars and take several decades to implement." Even if the facilities are available, many decades would be needed on the basis of current technology

[11] The minor actinides are neptunium, americium, curium, berkelium, and californium. The major actinides are plutonium and uranium.

to destroy even a fraction of the long-lived radionuclides already in the inventory. Most of the long-lived radionuclides would have to be recycled several times through a reactor or an accelerator to be destroyed to a significant degree. The facilities would produce nuclear waste streams of their own, many of which have yet to be well characterized.

The foregoing does not mean that there should not be an ongoing research and development program on partitioning and transmutation or that there are not opportunities for selectively implementing partitioning and transmutation in phases. In fact, partitioning and transmutation are ongoing at the international level: separating plutonium from commercial fuel by reprocessing and recycling the plutonium as mixed oxide fuel (MOX). Reprocessing commercial SNF is practiced in France, Russia, Japan, the United Kingdom, and in the past in the United States. The United States stopped reprocessing commercial SNF in 1972, when the Nuclear Fuel Services plant in West Valley, New York, shut down to perform plant upgrades. For regulatory, economic, and other reasons, the plant did not resume operating.

Reprocessing is being evaluated for its costs and benefits. The main concerns include economics and the effect of reprocessing on nuclear wastes. The price of the products of reprocessing, uranium and plutonium, is determined by the price of natural uranium. The current price of natural uranium is higher than the long-term average but considerably lower than recent peaks. Uranium resources appear ample at least until the end of the century (MIT 2010, NWTRB 2010). Compared with the once-through fuel cycle, reprocessing reduces somewhat the amount, radiotoxicity, and heat load of the high-activity waste requiring disposal. However, the isotopic quality of the uranium and plutonium recovered decreases each time that spent fuel is recycled, which makes multiple recycling increasingly impractical.

3. CONTRIBUTIONS FROM THE YUCCA MOUNTAIN PROGRAM

The history of Yucca Mountain as a potential repository site spanned more than 30 years, beginning officially in 1977, when Yucca Mountain was selected as one of several candidates to be investigated for the nation's first deep geologic repository for disposal of high-activity waste (DOE 1986a). In 1987, Congress directed DOE to study only Yucca Mountain (Congress 1987b). Site characterization occupied the 1977–2000 period for the most part, while the last decade consisted mostly of license application activities and related project engineering. Site characterization consisted mostly of scientific investigations of the geology and of the materials that would constitute the engineered barrier system. There was some engineering effort during site characterization, but it was of a very preliminary nature. Scientific activities decreased during the 2000–2010 period. The emphasis for science was consolidating information obtained and using it in computer models to demonstrate the safety of a Yucca Mountain repository. Little new data were gathered during the last 10 years, and much of the data came from ongoing existing experiments. Yucca Mountain graduated from a *concept* to a *project* at approximately the turn of the century, albeit a very large, very expensive, first-of-a-kind project.

The site-characterization phase of the Yucca Mountain program officially ended in 2002: Secretary of Energy Spencer Abraham recommended the site to President George W. Bush in February (Abraham 2002), and the President recommended the site to Congress, also in February (Bush 2002). In July 2002, acting on the President's recommendation, Congress gave DOE the authority to prepare and submit a license application for constructing a repository at Yucca Mountain (Congress 2002). DOE submitted the license application in June 2008, and the Nuclear Regulatory Commission accepted it for review three months later (DOE 2008a; Nuclear Regulatory Commission 2008). DOE requested permission to withdraw the application in March 2010, and the Nuclear Regulatory Commission staff performing the review were directed in October 2010 to make the transition to an orderly close-out (Irwin et al. 2010a; Jaczko 2010).

Although site characterization ended officially in 2002, DOE began steps to facilitate the transition in program emphasis from site characterization to licensing and engineering several years earlier. For example, in 1999, DOE decided to recompete its contract for a management and operating contractor (Barrett 1999) with a new contract focusing on a licensing and design work scope (Itkin 2000). The new management and operating contractor, a team led by Bechtel SAIC Company, LLC, replaced a contractor team led by TRW Environmental Safety Systems, Inc., in late 2000.

In this chapter, the Board discusses contributions to future repository programs from both the site-characterization phase and the license-application phase of the Yucca Mountain program, including its related project engineering.

3.1. MATERIALS AND ENVIRONMENTS OF THE ENGINEERED BARRIER SYSTEM

Robust Waste Package Design

DOE's Office of Civilian Radioactive Waste Management was investigating three potential repository sites in the mid-1980s: a bedded salt site in Deaf Smith County, Texas; a basalt site at Hanford, Washington; and a tuff site at Yucca Mountain in Nevada. Because the emphasis was on obtaining geologic data for comparing the three sites, relatively little attention was paid to the waste package that could be used at any of the candidate sites.

The original conceptual EBS design for the Yucca Mountain site called for only a thin-walled stainless-steel waste package that would have a limited life. Conceptual designs of waste packages for the other two sites were similarly short-lived. In fact, Nuclear Regulatory Commission regulations in effect for repositories at the time[12] appeared to limit the credit that could be taken for the waste packages to no more than 1,000 years—the approximate maximum duration of the thermal pulse.[13]

In July 1990,[14] the Nuclear Regulatory Commission clarified that the regulations did allow robust waste packages, i.e., waste packages that could last longer than 1,000 years. In its November 1990 report to Congress and the Secretary of Energy, the Board recommended that DOE adopt a long-lived, robust EBS and that DOE conduct a workshop on the "… practicality, advantages, and disadvantages of a robust, extended-life EBS" (NWTRB 1990). Part of the Board's reasoning underlying the recommendation was that the fabrication and materials of construction of the waste package would be controllable and therefore the behavior of the waste packages over time would be predictable. DOE held a workshop on robust engineered barriers in Denver, Colorado, in June 1991, and adopted a robust waste package design and discarded the thin-wall design by the end of the following year. The

[12] See 10 CFR 60(a)(1)(ii)(A).

[13] The thermal pulse is the period when waste package surface temperatures are substantially above ambient at repository depth. For Yucca Mountain, the thermal pulse begins when the repository is closed and lasts until waste package surface temperatures drop below 100°C. The duration of the thermal pulse for a waste package depends on the age of the high-activity waste in the package, the position of the package in the repository, and many other variables. For Yucca Mountain, the thermal pulse for some of the packages in the central area of the repository could last as long as 1,000 years.

[14] Nuclear Regulatory Commission Staff Position Paper 60-001; July 27 1990.

Board believes that the reasoning for its advocacy of a robust waste package applies to many if not all future repositories, and thus the Board recommends that future U.S. repository programs consider robust waste packages, regardless of the site chosen.

The robust waste package design adopted by DOE in 1992 had two walls: a moderately thick inner wall of corrosion-resistant alloy, e.g., 1 in. of Alloy 825; and a thick outer wall of either a corrosion-allowance material, e.g., 3 in. of carbon steel, or another corrosion-resistant material, e.g., 3 in. of a cupronickel alloy. The design adopted in 1992 went through changes in materials of construction, wall thicknesses, and other variables before the final design used in the license application was arrived at in early 1999. The final design has a 2-in. inner wall of 316 stainless steel and a 1-in. outer wall of Alloy 22 (a corrosion-resistant nickel alloy; see **Figure 3**). The waste package is cylindrical and has outer dimensions approximately 6 ft. in diameter and 15 ft. in length. It can hold 21 PWR assemblies or 44 BWR assemblies. A waste package of the size adopted by the Yucca Mountain program, although large enough for a transport-aging-disposal (TAD) canister, would not be able to accommodate canisters currently used in dry-storage systems.[15] *Future repository developers should ensure that repository designs, waste package sizes, and the sizes of canisters used in dry-storage systems are compatible, if feasible.*

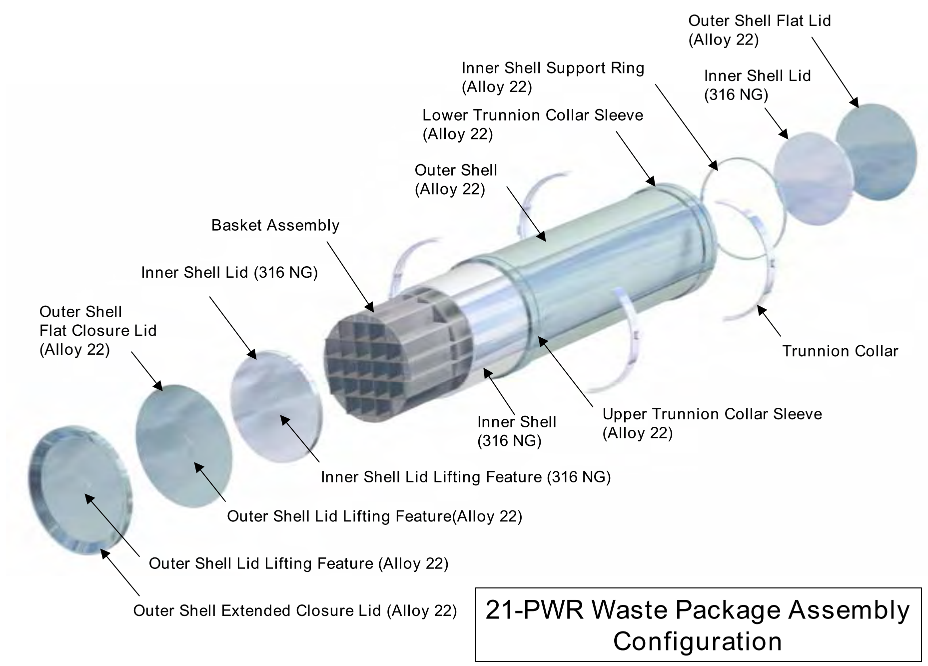

Fig. 3 Final Robust Waste Package Design (Russell 2000)

The Roles of the Engineered Barrier System and the Natural System

The defense-in-depth principle—using multiple independent, redundant barriers to achieve a safety goal—is a hallmark of complex systems, whether they are software, space exploration, security, nuclear power plants, or geologic repositories. The EBS proposed for the Yucca Mountain repository has many barriers including, more-or-less from inside out, the following:

[15]TAD canisters are discussed in section 3.5. The maximum weight of a waste package containing 21 PWR assemblies in a TAD canister is approximately 74 metric tons.

- the solid high-activity waste itself, which degrades and releases radionuclide slowly when exposed to water
- the cladding surrounding SNF or the canister containing vitrified HLW
- the stainless-steel TAD canister for commercial SNF
- the stainless-steel inner vessel of the waste package
- the Alloy-22 outer vessel of the waste package
- corrosion products formed if water penetrates the waste package and which can adsorb radionuclides and form a barrier to water flow
- aggregate and corrosion products in the EBS outside of the waste package, which also absorb radionuclides
- the titanium drip shield.

The natural system also has many barriers, including the following:

- slow average flow rate in the unsaturated rock zone between the repository and the water table
- radionuclide-adsorbing zeolites below the repository
- slow flow rate in the saturated zone
- a long distance (18 km) in the saturated zone from below the repository to the accessible environment.

The importance of individual barriers varies. The difficulty of characterizing and modeling individual barriers also varies. DOE did not take credit for some barriers because of their relative unimportance or difficulty characterizing and modeling them: e.g., SNF cladding and zeolites in the unsaturated zone beneath the repository.

Examination of the performance assessment and environmental assessment documents submitted as part of the license application and of recent presentations by DOE and its contractors at Board meetings shows the relative importance of various barriers (SNL 2008a; NWTRB 2008). Although the unsaturated zone beneath the repository and the saturated zone extending from below the repository to the accessible environment are formidable barriers, the drip shield and the waste package are much more important. That is, they are predicted to delay the release of radionuclides for much longer times.

Examinations of the documents and presentations also show the relationship between the EBS and the natural system: Although the natural system contains several important barriers, its principal role at Yucca Mountain is to provide a stable, predictable, and relatively benign "home" in which the EBS can delay any radionuclide release for many tens of thousands of years and, when releases finally do occur, to ensure that they occur very slowly.[16] *A lesson to be learned is that engineered barriers have the potential to be used to overcome weaknesses in natural barriers.* The respective roles of engineered barriers and natural barriers at other sites or in other geologic media can be different, as discussed in subsection 4.2 of chapter 4.

Predictability of the Rate of General Corrosion for Long Periods in Known Environments

Stainless steel and nickel-based alloys depend on a thin passive layer of oxides and oxyhydroxides for protection from corrosion. The layer blocks or severely retards the ability of oxygen or water to penetrate to and react with the alloy. If liquid water is present, general corrosion (also known as "uniform corrosion") always occurs in oxidizing environments, even if conditions are benign (e.g., room temperature, neutral pH, low concentrations of dissolved salts in the water). The rate of general corrosion may be extremely low in such conditions, however. Localized corrosion or stress corrosion cracking, in contrast, usually requires more-aggressive environments and other features, such as small occluded areas on the waste package surface, areas of high tensile stress, or small areas where halides concentrate. If localized corrosion or stress corrosion cracking occurs, it can proceed rapidly.

Assuming that the environments to which waste packages will be exposed over time are known or bounded, the general-corrosion behavior of the packages over long periods is predictable. Before the Yucca Mountain program, little thought had been given to the question of whether waste packages constructed from metals or alloys protected by passivity could be designed to last hundreds of thousands of years. The Yucca Mountain program presented evidence that such waste packages could be designed, depending on the repository environment and the avoidance of localized corrosion or stress corrosion cracking. The evidence included multiyear corrosion data in environments relevant to Yucca Mountain and models based on accepted physical principles (SNL 2007a). This experience allows confidence that future repository programs may be able to take advantage of very-long-lived waste packages.

Studies of waste package corrosion evolved in important ways as data were obtained, understanding of the waste package environment increased, the role of the waste package

[16] Whether DOE successfully established that the EBS could achieve its role would have been decided by the Nuclear Regulatory Commission during licensing. The outcome of the licensing process would have determined whether the engineered system could compensate for site shortcomings—an important generic technical lesson that was a principal reason that the Board supported continuing the licensing process regardless of the nation's direction on nuclear waste disposal (NWTRB 2009a).

changed, and the standard changed from 10,000 years to 1,000,000 years. Initially, the program staff appeared not to believe that liquid water (necessary for significant corrosion to occur) could exist at temperatures well above 100°C. Liquid water at temperatures well above 100°C will occur if certain combinations of common salts are in the dusts deposited on waste packages by ventilation air during the period following emplacement but before repository closure.

*If the waste package is an important **long-term** barrier in future repository programs, corrosion investigators and repository environment investigators should reexamine the Yucca Mountain experience, should be flexible and adaptable as new data are obtained and as requirements for waste package performance change, and should use care to ensure that sufficient understanding exists of elevated temperatures where liquid water could be present in the form of concentrated multicomponent brines.*

To summarize, isolation of wastes by corrosion-resistant, nickel-rich (Alloy-22) containers provides the principal radionuclide isolation in DOE's quantitative performance models for the proposed Yucca Mountain repository. Because waste package materials and fabrication methods can be carefully controlled, analyzing the behavior of the waste package and predicting its lifetime are tractable, provided that localized corrosion and stress corrosion cracking can be prevented. If the waste package is also robust (thick-walled), the lifetime of the waste package may be extended. Although still dwarfed by the "lifetime" of the natural system, a waste package with a million-year-plus lifetime is very important because only a very few radionuclides with extremely long half-lives (e.g., ^{242}Pu, ^{237}Np, ^{129}I, with half-lives of 0.38 million years, 2.14 million years, and 15.7 million years, respectively) remain. Moreover, because temperatures can be expected to be low, 25 to 30°C, when packages do fail and because the natural environment will have returned to its ambient state before being disturbed by repository construction and decay heat, analysis of the source term may be simplified. Of course, no matter how carefully controlled the materials and fabrication of the waste package, corrosion behavior cannot be predicted accurately and confidently unless the environment is also known well, or at least bounded.

Corrosion Technical Management

Although the Yucca Mountain program never lacked highly capable corrosion scientists and engineers, its technical management of corrosion was at times deficient. This was particularly the case during the period beginning in the late 1990s and extending into 2006. This was a period that began with the waste package being one of several engineered and natural barriers in a 10,000-year repository and ended with the waste package being arguably the most important engineered barrier in a 1,000,000-year repository. There were several possible reasons for the subpar corrosion management: (1) Diffusion of authority and responsibility for corrosion among DOE, DOE's support contractor, DOE's management and operating (M&O) contractor, and the National Laboratories performing corrosion-related work; (2) Lack of continuity, particularly due to retirements of key personnel, changes in M&O contractors, changes in reporting relationships between the M&O contractor and the National Laboratories, and the move to a lead laboratory; and (3) Inconsistency in funding for corrosion activities, which made attracting and retaining senior corrosion managers difficult.

The lack of continuous strong corrosion leadership hampered the program. For example, in the late 1990s, it became evident that water could exist on waste package surfaces because of the elevation of boiling point from concentrated salt solutions (brines) formed by the deliquescence of salts carried into the repository in ventilation air during the preclosure period, a period anticipated to last at least 50 years. New corrosion tests had to be devised in the laboratory to address the higher-temperature conditions. Many of the new tests were done in concentrated solutions of pure calcium chloride (SNL 2007a), a poor choice because pure calcium chloride solutions are unlikely to exist at Yucca Mountain. More likely, because the salts entrained in the ventilation air would be a mixture of salts, including calcium chloride, the brines resulting from their deliquescence would be a mixture of several salts dissolved in water. The fact that so many of the tests were performed in calcium chloride solutions rather than in more realistic mixed-salt solutions is an indicator of weak corrosion management.

For future repository programs where corrosion is important, the Board recommends that strong technical corrosion management be established at the inception of investigations and maintained not only throughout the investigations but also throughout subsequent program phases, including site-suitability determination, license-application preparation and review, construction, operation, performance confirmation, and closure.

Flexibility of Test Plans Because of External Changes

DOE assigned responsibility for research on and modeling of corrosion of waste-package materials for a Yucca Mountain repository to Lawrence Livermore National Laboratory (LLNL) in the early 1980s. LLNL carried out literature studies on degradation modes of potential waste package materials during the 1980s, conducted limited corrosion research, and developed a long-range plan for corrosion research during this same period. A major part of the plan was the construction and operation of a long-term corrosion test facility (LTCTF) in which samples of candidate materials would be exposed to simulated Yucca Mountain environments in stirred baths for multiyear periods and their corrosion modes and rates determined after the exposures. The LTCTF was designed, approved, and constructed, and the first samples were placed in it in 1995. Eventually, more than 12,000 samples were placed in the LTCTF. The LTCTF continued operating until 2005.

Enactment of the Energy Policy Act of 1992 set in motion a complex and lengthy process that ultimately resulted in revised regulations applying to a high-level-waste repository located at Yucca Mountain. Taken together, two of the revisions increased the importance of the waste package significantly. Those revisions were (1) the performance of the repository as a total system was specified to be the principal measure of the merit of the repository (Nuclear Regulatory Commission 2001) and (2) the period for determining the performance of the repository was specified as a million years (EPA 2008). Before the revisions, there had been individual requirements for subsystems of the repository, and the period of performance had been limited to 10,000 years. Although the changes were formally adopted well after commencement of LTCTF operations, they were very much a matter of discussion in the mid- and late 1990s. In fact, a special panel of the National Research Council recommended in a 1995 publication (NRC 1995) that the period of performance for Yucca Mountain be until the time of peak risk[17]—essentially repeating a recommendation made for all repositories by another National Research Council panel in a 1983 publication (NRC 1983).

Board members having special expertise and interest in corrosion have monitored DOE's technical activities in the corrosion area closely over the years, visiting LLNL and the LTCTF several times, discussing corrosion matters with the Yucca Mountain program staff, and receiving periodic updates on corrosion-related activities at public meetings of the full Board or its panels. To the Board's knowledge, the Yucca Mountain program's corrosion management did not conduct a review of the LTCTF to determine whether the data it had produced and would produce would be adequate for the increased importance of the waste package. However, Sandia National Laboratories (SNL) took over corrosion responsibilities in late 2006 and began to scrutinize the LTCTF methodology and data. Several problems were found, which SNL personnel documented in "Condition Reports" (SNL 2008b; SNL 2009). Although much of the data are still usable, some have had to be discarded, namely general-corrosion data based on crevice samples exposed for 5 years in the LTCTF and all samples exposed for 9.5 years in the LTCTF. The data based on 5-year crevice samples were rejected because of uncertainties about whether the samples had been cleaned completely before being weighed in 2002-2003 to determine weight loss. The 9.5-year data were rejected because of the presence of visible deposits of stirrer gear-reduction box grease on many of the samples. As a result of rejection of two sets of data, the case for the longevity of the waste packages with regard to general corrosion of Alloy 22 at below-boiling temperatures, although still strong, is not as strong as it once appeared to be.

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[17] Within the limits of geologic stability of Yucca Mountain, which the panel judged was "on the order of one million years" (NRC 1995).

The lesson learned in this case is that quality-control measures for long-term experiments need to be improved and established at the beginning of any research program to be assured that they pass the rigor of regulatory expectations.

Whether an examination of the LTCTF procedures when the changes to the regulations were being discussed rather than after the regulations were formally adopted could have resulted in changes to the LTCTF that would allow all of its data to be used is not known. Nevertheless, the lesson for future repository programs is clear and applies to all technical areas, not just corrosion: *Test plans and equipment should be reexamined when changes external to the program are being considered.*

Dust in Repository Ventilation Air

The corrosion environment for waste packages is affected by dust brought in by ventilation air during the preclosure period. The conceptual description of the waste package corrosion environment due to the deposition of atmospheric dust on the metal during preclosure ventilation evolved considerably over the life of the Yucca Mountain program. What has changed is the description of the composition of the dust, what happens to the dust in a chemical-reaction sense, and the effect of radiolysis. That the dust layer on waste package surfaces is a dynamic reacting chemical system with a continual supply of reactants has been known for about 10 years. The dust on waste package surfaces may evolve into a brine by dissolving into water that drips onto the waste packages or via deliquescence by reacting with moisture in the air. The brine could cause or exacerbate corrosion, particularly fast-acting localized corrosion. For this reason, having a complete conceptual description of the corrosion environment on waste package surfaces is vital.

At least five major factors affect the evolution of the conceptualization of the corrosion environment on a waste package as affected by atmospheric dust, including the existence of calcium chloride in and on atmospheric dust; the existence of organic matter in and on atmospheric dust; the reaction of organic matter with nitrate in dust, depleting the nitrate content; radiolysis effects, including gamma radiation of halide salts producing halogen gases; and radiolysis of moist air producing oxides of nitrogen, specifically nitric acid. Examination of the details of these major factors leads to the conclusion that understanding of the corrosion environment as described at the time of the *License Application Design Selection Report* (CRWMS M&O 1999b) was incomplete.

The conceptual description of the corrosion environment of a waste package determined in part by atmospheric dust clearly has evolved in comparison to the description of 10 years ago. The experience gained in this evolution applies to a description of any corrosion environment that results from exposure to the atmosphere, especially that expected for the long-term dry storage of SNF on the Earth's surface, where natural-convection cooling using the atmosphere is expected to be implemented. Many, possibly all, future repositories may have extended preclosure periods. That is, the duration of the time between emplacement of a waste package and closure of the repository may be measured in many decades, if not centuries. In some repositories, dust could be deposited on waste package surfaces during that period, and the composition of the deposited dust would be affected by the major factors mentioned above.

The composition of dust or other deposits from the natural environment determines the corrosion environment during the preclosure period and influences the corrosion environment during the period that begins immediately after closure. Thus, studying the evolution of the waste package surface environment is important for any future repository.

A more detailed analysis of the evolution of the environment on waste package surfaces due to dust entrained in ventilation air is in Appendix A-1.

3.2. SOURCE-TERM QUANTIFICATION

For this discussion, the source term is defined as the radionuclides released to the natural system from the EBS. Murphy, Garrick, and Kirstein (2009) characterized the principal mechanisms of radionuclide isolation or release-rate reduction at the source for the proposed Yucca Mountain repository to be (1) diversion of water flow around the drift; (2) diversion of water flow by the drip shield (see **Figure 4**); (3) isolation of wastes by containers; (4) stability of the waste form(s); and (5) sequestration of radionuclides in products of waste package alteration. Although studies for the Yucca Mountain program (e.g., SNL 2007b) made significant advances in quantifying each of these isolation mechanisms, room for improvement in the realism of the quantifications exists, particularly for (4), as described later in this section.

Figure 4. Titanium Drip Shield

Research supporting the Yucca Mountain program led to advances in quantitative understanding of groundwater flow in fractured hydrologically unsaturated rock (e.g., Flint et al. 2001a, b). This understanding was used to model flow of water around and through waste-emplacement drifts. Major advances also were made in modeling transient heat and two-phase (gas and liquid) fluid flow in the geologic media around heat-producing wastes in the proposed repository (e.g., Buscheck 2002, 2005). Repository design was modified to take advantage of thermo-hydrologic effects: for example, by adoption of line-loading thermal management (CRWMS 1999b).

The drip shield concept is unique to Yucca Mountain. Drip shields composed of corrosion-resistant titanium were incorporated in the EBS to protect waste packages from water flow and to prevent or retard mobilization of any radionuclides escaping from prematurely failed waste packages. Drip shields are predicted to make a significant contribution in quantitative estimates of the Yucca Mountain repository's performance (SNL 2008a).[18]

Theoretical studies of the thermodynamic stability of crystalline UO_2, experimental studies of the alteration rate of SNF, and studies of the oxidative alteration of natural uraninite deposits in environments analogous to Yucca Mountain provided converging lines of evidence that SNF in the Yucca Mountain environment would alter by oxidation in a time frame that is short in comparison to its radiological hazard (e.g., Murphy 2000). Performance assessments used rates of waste-form alteration based on experimental data to define release rates of high-solubility radionuclides from the EBS to the natural system (SNL 2008a). Despite the fact that zircaloy is highly corrosion resistant in the Yucca Mountain environmental conditions likely at the time of contact of zircaloy cladding by water, no credit was taken for zircaloy cladding in the total system performance assessment for license application (TSPA-LA).

Reaction of EBS materials, e.g., waste packages and waste forms, with gas, water, and rocks in the Yucca Mountain environment could produce relatively stable materials with the capacity to sequester some radionuclides for indefinite periods. Solubility limits of radionuclides were quantified for source-term evaluations for the proposed repository (Bernot 2007). Sequestration in the waste package, but not in the EBS outside the waste package, also was modeled (BSC 2005). Variability and uncertainty in near-field environmental conditions and particularly in the compositions and properties of solid-phase alteration products led to uncertainties spanning many orders of magnitude in radionuclide concentrations in groundwater solutions (SNL 2008a). More accurate characterization of coprecipitation of radionuclides in thermodynamically stable secondary solids could have improved quantitative estimates of repository performance (e.g., Murphy and Grambow 2008). The rate of diffusive transport of radionuclides through waste package alteration materials provides transient retardation of radionuclide migration to the natural environment in performance-assessment models (SNL 2008a).

A repository developer should achieve a balance of the factors contributing to the performance of a permanent disposal system. For example, a key calculation of the performance of any repository is the fractional release rate of radionuclides from the EBS to the natural system

[18] It should be noted that the importance of the drip shield to repository performance is based on the assessment made in the total system performance assessment that was part of the license application.

as a function of time—quantification of the source term. By “balance” is meant comparable confidence in the representation of the various steps of the source-term calculation. The drip shield and the waste package eventually will fail to the point where they allow water to reach the high-activity waste. Because of many conservative assumptions,[19] the portrayal of degradation, mineralization, sorption, transport, dissolution, mobilization, and sequestration of the waste form or its radionuclides as a function of the changing environment and time in the models and analyses included in the license application and its supporting materials was unrealistic. The outcome of the source-term model might have been very different if its processes had been modeled differently. Certainly, the confidence in the realism of the analysis would have been different.

The form and rate of radionuclides entering the natural system are critical to assessing repository performance. In particular, the form determines their behavior in the natural system. Transport, retardation, and sequestering need to be quantified to answer the risk question. There is a need to consider the possibility of different chemical and mineral forms of radionuclides released into the natural system and, in the spirit of risk assessment, to determine the likelihood of receiving different radiation-dose levels on the basis of the supporting evidence, while quantifying the uncertainties in the probabilities.

The source term should be quantified and realistically assessed. A realistic assessment is important to a fundamental understanding of barrier performance and the radionuclide forms entering the natural system.

In the proposed Yucca Mountain repository, the drip shields and the waste packages are very important to the assessed performance of the repository. Because of their predicted longevity, they delay the possibility of mobilization of the waste for many hundreds of thousands of years until the burden of isolating the waste shifts to the waste form, the interaction between radionuclides released from the waste form and corrosion products or other materials in the EBS, and, eventually, the natural system. Thus, quantifying the isolation capability of the EBS is important to obtaining greater quantification of the source term. The Board believes that a much more realistic assessment of the EBS—and therefore the source term—is possible than was provided for the proposed Yucca Mountain repository.

Because the modeling and simplifying assumptions for radionuclide mobilization and transport in the EBS were conservative, characterization of the source term was unrealistic. Although a great deal of effort was expended by the Yucca Mountain program on modeling the source term, the effect of anthropogenic materials (e.g., the metals of the waste package,

[19] Examples of conservatisms include no corrosion resistance of the stainless-steel waste package inner vessel or the stainless-steel TAD canister; no corrosion resistance of the zircaloy cladding; no plugging of waste package breaches by corrosion products; and no effect due to corrosion products in the invert.

the pallet, and the invert[20]) on the waste-form environment was not taken fully into account in TSPA-LA (BSC 2005: 6-41).

In reality, the presence of abundant reduced material and the ability of corrosion products to limit the access of water and oxygen are likely to cause substantial lowering of the in-package reduction-oxidation potential. For example, despite strong evidence that the presence of large amounts of iron-based waste-package or invert materials significantly reduces the rate of degradation of uranium dioxide or spent fuel by making the local environment less oxidizing (Cui et al. 2009; Ferriss et al. 2009), the effect of these materials on the environment was only partially taken into account (SNL 2007b; Ap. VI).

A critical factor in the assessment of the performance of a repository, and thus the achievement of an optimal design, is quantifying the source term. The Yucca Mountain program placed too little emphasis on research on mobilization of the waste within the EBS compared with degradation of the waste package. A positive lesson to be learned for future repositories is the potential importance of the source term and the need to understand it well. The source term more than anything else determines the performance requirements of the natural system.

3.3. CHARACTERIZING AND MODELING THE NATURAL SYSTEM

The Value of Underground Research at Yucca Mountain

Determining the suitability of a site for an underground repository for radioactive waste requires a good understanding of the site's geology, potential future geologic processes at the site, and how the site could react to excavation and the decay heat of emplaced waste. Among other things, an ideal site would have rock that is spatially homogeneous[21] and without flaws, such as faults, over a volume large enough to accommodate a repository. However, because the underground rock is hidden from view, adequately characterizing site geology is a challenge. Unforeseen geologic features and conditions can greatly affect the cost, schedule, modeling, safety of workers, and performance of the repository.

In 1994, the Board held a meeting to review successes and failures of various attempts to site and license large engineering projects, such as nuclear repositories, power plants, and dams (NWTRB 1994). On the basis of the meeting and subsequent analysis, the Board offered several insights and lessons learned that it believed would be applicable to Yucca Mountain (NWTRB 1995): (1) Site assessment requires a strategy that is an iterative process that continually looks at the relationships among data gathering, modeling, and performance assessment; and (2) Expect surprises in any underground site investigation. Geologic

[20] The pallet (sometimes called the pedestal or the platform) is the cradle-like metal structure that supports the waste package in the repository. The invert is the built-up steel and backfill structure that rests on the floor of an emplacement drift and provides a flat surface for supporting rails and the pallet.

[21] "Homogeneous rock" refers to a body of rock that is structurally, physically, and chemically uniform in its spatial extent. Repository-size volumes of near-homogeneous rock are not uncommon in nature.

surprises did appear over the years of investigation at Yucca Mountain. A few examples are mentioned below. The surprises affected the evolving conceptual site model and repository design. DOE and the Yucca Mountain program remained sufficiently flexible to incorporate the surprises into project knowledge and modeling, but surprises sometimes led to project delays. Inevitably, any investigation of future repositories will encounter its share of surprises, and the understanding of the geology will evolve, particularly after underground access is provided. An illustration of one of the surprises—how the understanding of the geotechnical aspects of the rocks changed once investigators were able to get underground—is in Appendix A-2.

Surprises that surface and underground research at Yucca Mountain revealed include that some water infiltrating into the mountain moves through the unsaturated zone rapidly; that water composition in the unsaturated zone is heterogeneous and significantly different from the presumed water composition before extensive site characterization started; that water infiltrates at a significantly higher rate than thought when site characterization started; that extensive perched-water systems are present; and that there is channelized flow in the saturated zone. Although hydrologists never thought that the Yucca Mountain unsaturated zone was "dry," print and electronic media offered references to "dry" that may have numbered in the thousands. The idea of minimal infiltration in an arid environment among many unsaturated-zone hydrologists of the 1980s (e.g., Winograd 1981) pertained to the alluvium. Indeed, physical and chemical evidence from around Yucca Mountain indicates that net infiltration through thick alluvium is very close to zero. The site chosen for the Yucca Mountain repository, however, was fractured tuff with minimal soil cover, much different from the loose, unconsolidated nature of alluvium. Thus, despite the low precipitation at Yucca Mountain and the runoff and evapotranspiration of much of that precipitation, some infiltration occurs.

The principle of expecting surprises need not preclude successful site characterization and permanent high-activity waste disposal. For example, preconceived notions about the basic technical questions of salt creep rate, rock permeability, and water abundance at the WIPP site all were proven wrong once the underground exploration facility was constructed. Another surprise was the presence of pockets of pressurized brine near the WIPP site. Nevertheless, that site proves to be an acceptable one for the disposal of non-heat-generating transuranic waste. *Reasonable engineering accommodation to site-characterization reality worked for WIPP, just as a robust container may well have worked for Yucca Mountain.*

Hydrogeology of the Unsaturated Zone

The U.S. Geological Survey (USGS) suggested that disposal in the unsaturated zone would offer advantages in deep geologic disposal of high-activity waste, the thought being that a site with limited water flux downward would be a benefit to repository performance (e.g., Winograd 1974; Roseboom 1983). The deep water table and thick unsaturated zone at Yucca Mountain were thought to be indications of a very low infiltration rate and therefore a negligible downward flux; advective transport by water was, and still is, considered the most serious threat to mobilizing nuclear waste.

Studies at Yucca Mountain advanced scientific understanding of water flow in unsaturated fractured rock in arid regions. In particular, mass-balance methodology has been used to quantify infiltration and characterize the spatial distribution of net infiltration and recharge (Hevesi et al. 2002). In an arid environment, infiltration is the small difference between precipitation and water lost by runoff and evapotranspiration. The difference between the "input" and "output" flow is a few percent or less and can be locally negative, so quantification of the difference is difficult. Despite the advancements, room for additional improvement remains. For example, direct measurement of evapotranspiration still needs further development.

The independent development of analytical technology over the last two decades led to the use of microstratigraphic characterization and dating of secondary mineral deposits of calcite and opal in fractures and lithophysal cavities[22] at Yucca Mountain. The microstratigraphic characterization was done at the tens of microns scale to develop a chronology for millimeter-thick hydrogenic deposits formed over a period of longer than 10 million years (Paces 2004). The mechanism for the deposits is not fully understood, however. Percolating water increases in temperature because of the geothermal gradient at Yucca Mountain, leading to eventual precipitation of calcite because of its retrograde solubility. Silica has prograde solubility, however. Murphy (2009) suggests that evaporation due to the warming of descending gas could explain the apparent anomalies.

Modeling, using computers, was used extensively for project studies. Hydrologists developed models accounting for runoff, evaporation, plant transpiration, the effect of capillary forces, and other parameters. Various hypotheses were tested in the models, leading to improved insights on flow in unsaturated rock. The collection of models used for hydrology calculations underpinning performance assessments in the license application resulted from a decades-long iterative process of obtaining field data, testing various hypotheses, and refining the models. A significant modeling advance came in the coupling of multiphase transport in complex geologic media: The coupling of heat and fluid mass transport with provision for geochemical reactions in time and space allows modeling on time scales appropriate for consideration of nuclear waste disposal and sets the stage for future advances in modeling and understanding multiphase transport in geologic media.

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[22] *Lithophysal cavities* or *lithophysae* are hollow bubble-like structures of varying size found within some tuff.

Characterization of future repository sites that feature significant unsaturated zones will benefit greatly by the understanding developed as a result of characterization of Yucca Mountain's unsaturated zone.

Hydrogeology of the Saturated Zone

Characterization of Yucca Mountain hydrology also led to advances in understanding the saturated zone, including the effect of matrix diffusion on radionuclide transport. As in the unsaturated zone, transport in the saturated zone is through both fractured and unfractured porous media. Part of the saturated zone consists of tightly fractured or unfractured media, where matrix diffusion is the dominant mode of transport. In general, sorption is more important in matrix diffusion than in fracture flow because of the larger rock-surface area relative to the volume of water. Thus, matrix diffusion into adjacent unfractured rock can slow the rate of movement of radionuclides through the rock in comparison to the rate of water flow through fractures. Besides sorption of radionuclides onto mineral surfaces, precipitation of minerals as chemical conditions change along the flow path also can be important.

Understanding Thermal Management

In general, if the temperature of the waste package's outer surface is in the range that water exists as a liquid, the higher the temperature, the more rapid the degradation (corrosion) of the waste package.[23] Similarly, the higher the temperature of the waste form when it is contacted by liquid water, the more rapidly it will dissolve or radionuclides will leach from it. Theoretically, then, one would want to keep repository temperatures as low as possible for best performance. There are trade-offs, however. One strategy would be to keep the repository hot enough to keep water in a vapor state while the degree of hazard of the waste declines through radioactive decay. A disadvantage of this strategy, however, is that when the temperature eventually drops to the point where liquid water is possible, the duration of the period with high-temperature liquid water would be longer than if a low-temperature strategy were used.

High-activity waste generates heat as it undergoes radioactive decay. The effect of the decay heat on waste-form temperatures, waste-package temperatures, and repository-rock temperatures close to and far from the emplaced waste is most pronounced during the thermal pulse. How high temperatures rise during the thermal pulse and how long they

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[23] The gas pressure in a Yucca Mountain repository would be essentially atmospheric (~710 mm Hg at the altitude of the proposed repository). The lowest waste package outer surface temperature, which would not be reached until many thousands of years of cooling, is ~25°C. The highest temperature at which bulk liquid water could exist is approximately 150°C, although there is uncertainty about this figure. At atmospheric pressure and 150°C, water would need to be in the form of a concentrated, multicomponent brine with significant divalent halide or nitrate content to be liquid. Minerals necessary to form such a brine may not be present in the rock but may be carried into the repository as part of the dust in ventilation air. If temperatures are so high that liquid water cannot exist, there will be no corrosion by liquid water and no possibility of waste-form dissolution.

stay elevated depend on a large number of variables, including the thermal conductivity and degree of saturation of the rock, the design of the waste packages, the amount of waste in each waste package, the location of the package in the repository, how closely waste packages are placed to each other, the type and age of the waste at emplacement, the amount of ventilation before repository closure, the permeability to convective gas flow of the rock and drifts through the rock, and many other variables. Many of these variables are design variables, that is, they are at least partially under the control of the designer or operator of the repository. The spacing of waste packages is an example of a design variable. Other variables are not design variables, i.e., they cannot be controlled by the repository designer or operator. An example is the thermal conductivity of the rock.

The Yucca Mountain program engineers investigated many alternatives for controlling the temperatures in the repository (e.g., CRWMS M&O 1999a). Independently, Nye County contractors investigated both similar alternatives and different alternatives consisting of novel ventilation schemes (Danko 1997; Danko et al. 2004). The work of the Yucca Mountain engineers and the Nye County contractors established that there are many different ways to meet thermal goals and constraints and to select from for developing a preferred system. Future repository system designers can learn from the Yucca Mountain experience.

On the basis of the analyses of its engineers, contractors, and others, DOE management made the fundamental decision that the Yucca Mountain repository would be based on a high-temperature design (Barrett 1999). Waste package surface temperatures would rise rapidly to above-boiling levels within a few years after repository closure and would remain above boiling for 50 to 1,000 years, depending on the position of the package in the repository, the waste loading in the waste package, and other variables. The factors underlying the decision, such as cost, licenseability, data availability, uncertainty, and others, were discussed at a Board meeting on repository design in Beatty, Nevada (NWTRB 1999). The decision on repository temperature is one that future repository developers face, and it is a difficult one to make because it must balance the value of continued radioactive decay and the time to peak temperature and subsequent water ingress in the repository horizon upon cooldown.

Thermal Analysis

Data are needed to construct models of corrosion, solubility, and dissolution rates. If the temperature range over which liquid water would be encountered is wide, more data are needed to construct the models than for a narrower temperature range. Ideally, one would have data that cover the full range of environmental conditions (temperature, pressure, water composition) that waste packages and waste forms would encounter. If not, extrapolation is necessary. Extrapolation from the 65 to 90°C range, where the bulk of the Yucca Mountain program's corrosion data exist, down to 25°C presents little risk because phenomena and mechanisms in this range are understood. Extrapolation up from the 65 to 90°C range, however, presents greater risk because possible phenomena and mechanisms are less well known, particularly for temperatures above 100°C and particularly when water containing dissolved salts is at its boiling point. Data are easiest to gather at low temperatures, and much data already are available in the technical literature for temperatures of 25 to 50°C. As temperatures increase from this level, however, corrosion, solubility, or dissolution-rate data become scarce. Data are particularly scarce at temperatures near or above the boiling point of pure water. Water can be a liquid well above the boiling point of pure water if the water is in the form of a concentrated brine (e.g., Hoffmann and Voigt 1996).

Thermal-analysis models and computation tools used at Yucca Mountain improved considerably over the last 20 years. The tools became much more efficient, which allowed more detail to be included in models, which in turn led to better understanding of how temperature profiles could change over time. Accurate estimates of thermal conductivity are crucial for temperature profiles in a repository. Improved understanding of the thermal conductivity of wet and dry lithophysal tuff (both bulk rock and crushed tuff) resulted from the improved computational tools, as did improved understanding of the transport of heat and mass in the waste-package environment. One of the Board's contributions to the rapid and efficient computation of repository temperatures is described in detail in Appendix A-3.

Natural Analog Studies

Studies of natural analogs, particularly the Peña Blanca uranium ore deposit in northern Mexico, contributed to a better understanding of the long-term processes that are relevant to Yucca Mountain and of the long-term stability of minerals in arid regions, particularly the uranyl minerals. The studies contributed to a more fundamental understanding of climatic, geologic, and hydrologic processes that could affect repository performance in unsaturated zones; this applies to nuclear wastes as well as to other wastes (which are much more voluminous, and many of which have "infinite" half-lives). A particularly valuable result of natural analog studies for Yucca Mountain was demonstration of converging lines of evidence with respect to the geochemical evolution of the repository when compared with Yucca Mountain site characterization and associated experimental studies (e.g., Murphy 2000). Other examples of natural analogs include the underground cities of Cappodocia, Turkey, and Egyptian tombs, which show that capillary barriers can persist over long time periods. Although such examples are largely anecdotal, they lend credence to claims of a capillary-barrier effect in the drifts at Yucca Mountain. *Natural analogs proved invaluable for the Yucca Mountain program and may well be so for future repository programs. Natural analogs should be identified and studies on them initiated early in the site-characterization programs of future geologic repositories.*

The USGS recently published an excellent compendium of natural analogs (Simmons and Stuckless 2010). Although focused on analogs relevant to repositories in unsaturated rock, the compendium should be useful for any future repository program. Natural analogs can be tools for demonstrating why scientists believe their predictions.

Solubilities of Uranyl and Neptunyl Minerals

Experimental and theoretical work related to site characterization advanced understanding of the thermodynamic properties of uranyl minerals and the trace solubility of neptunyl in these phases (e.g., Murphy and Grambow 2008). As with many aspects of the Yucca Mountain natural system, additional work would improve understanding. SNL (2007c) states that evidence for incorporating neptunium into uranyl structures has been investigated only for some uranium(VI) corrosion products, the nature of the neptunium association with uranyl solids has not been unambiguously determined, and the effect of such association on dissolved concentrations of neptunium, particularly in the long term, has not been addressed experimentally. SNL also proposes a large number of experiments to obtain the following quantitative data about potentially relevant neptunium-bearing solids: (1) solubilities and thermodynamic stabilities in water chemistries expected in a repository; (2) equilibrium partitioning of neptunium between relevant solids and aqueous solutions as a function of solution chemistry, and possibly as a function of solid chemistry as well; and (3) precipitation and dissolution rates for all relevant neptunium-bearing solids. *Because uranium, neptunium, or uranium-neptunium secondary minerals may be major contributors to long-term dose in future repositories, the continued study of their solubilities is warranted.*

Seismic and Volcanic Considerations

The Yucca Mountain program contributed to how to use mapping and other studies for locating faults and evidence of past volcanic activity in the vicinity of potential disposal locations. The location, timing, and amount of movement on these faults and periods of volcanism were characterized as part of the hazard analysis. A major contribution was made to the process of expert elicitation as a method of developing a more fundamental understanding of phenomena such as seismic and volcanic risks and as defensible input to calculating the risk of seismic events of varying severities and volcanic eruptions in confined and unconfined spaces. A diagnostic science was developed by using precarious rocks (precariously balanced rocks likely to be toppled by strong-enough seismic activity) as strong-motion seismoscopes at the Earth's surface to constrain the probability of seismic ground motions (Brune and Whitney 2000). Seismic and igneous understanding gained while characterizing Yucca Mountain will benefit future repository programs located in active seismic areas or in areas that have had geologically recent igneous activity.

The Yucca Mountain program significantly advanced the state of scientific knowledge in several areas related to seismic and igneous hazards. In these areas, rigorous state-of-the-art expert elicitations and probabilistic seismic and volcanic hazard analyses led to significantly more robust fundamental understanding of the phenomena and substantially improved technical bases for risk calculations.[24] (According to the license application, some of the greatest risks result from low-probability, high-consequence events in the igneous and seismic scenarios.) *Future repository risk also may be driven by extremely low likelihood and potentially high-consequence events, which suggests that they be considered a primary technical factor for repository siting determinations.*

Performance Confirmation

In submitting its license application to the Nuclear Regulatory Commission in June 2008, DOE was attesting to its belief that its natural-system characterization and modeling met compliance requirements. *Research on the natural system did not stop at that point, however, for two reasons. First, Nuclear Regulatory Commission regulations require a continuing research program (known as a "performance confirmation program") as a condition for granting the license to construct the repository.* The purpose of the program, as its name implies, would be to evaluate the adequacy of assumptions, data, and analyses underlying the construction license. The program and subsequent programs specified under a license to operate would continue until repository closure, which could be well over a 100 years after emplacement of the first unit of waste in the repository. The second reason for continued research on the natural system is to increase understanding of its behavior. *Increased understanding can lead to reduced uncertainty and greater confidence in the technical community about repository behavior.* Increased public confidence was a major reason for the Science and Technology program that OCRWM initiated in 2002 (Chu 2002).

Designing and Excavating Site-Characterization Facilities

The 1993 DOE site-characterization annual plan included plans for extensive tunneling into the planned geologic repository block to gain visual and testing access to the site's geology (NWTRB 1993: 2). Before the beginning of underground tunneling in 1994, surface-based testing consisted of trenching, outcrop examination, and vertical boreholes that provided almost 200 small-diameter (1- and 2-inch) cylindrical specimens to test geophysical access, but most of the boreholes were located outside the repository-block boundary and had orientation and other limitations. The importance of direct tunneling into the mountain was emphasized by the Board (NWTRB 1992: 16-17) because the tunneling provided

[24] For example, in 2008 DOE's lead laboratory issued a probabilistic volcanic-hazard assessment update that resulted from a rigorous four-year study (SNL 2008e). The study methodology (closely following U.S. Nuclear Regulatory Commission guidance on using expert elicitation in probabilistic hazard assessment [Kotra et al. 1996; Budnitz et al. 1997]) was based on a formalized expert elicitation and included a series of independent expert briefings in which all available data and interpretations were presented and considered, multiple field excursions were conducted, and aggregated and weighted conceptual and numerical models were produced and analyzed. The study drew on state-of-the-art data and analytical techniques in both geosciences and statistics. The 2008 study, which included consideration of repository disruption by dikes, sills, and erupting columns and vents, estimated the probability of repository disruption as 3.1×10^{-8} per year, slightly higher than previous estimates.

opportunities for exploring continuous sections of the repository block to identify geologic features, obtaining representative-size specimens for laboratory testing, and conducting in situ performance field-testing.

The Yucca Mountain program's exploratory tunnel was delayed and incurred high costs because of DOE decisions to contract for larger-than-normal custom excavating equipment and not to consult and incorporate the experience of practicing specialists at early stages (NWTRB 1993: 22-24). Part of the reason for the decisions may have been a perceived pressure to build the repository. DOE opted for large tunnel diameters in 1990 (NWTRB 1992:16) and contracted for the construction of a 7.6 m- (25 ft.) diameter, special-design tunnel boring machine (TBM) to excavate the tunnel, named the exploratory studies facility (ESF). The Board was concerned that the tunnel diameter was overly large and that it would lead to higher costs and delays. The Board had suggested that the "tunnel size" (diameter) be no greater than functionally required for early access and exploration of the geologic block" (NWTRB 1992: 17). The most frequent argument made by DOE and the M&O contractor in support of large tunnels was that the large diameter was needed for possible ventilation purposes as part of the future repository design (NWTRB 1998: 15).

DOE excavated the large-diameter 7.9 km (4.89 mile) ESF tunnel over about 31 months, yielding a net production rate of about 12.3 m (40.4 ft.) per working day (NWTRB 1998: 15), which is slow compared with conventional tunneling (NWTRB 1993: 16) and considerably lower than the planned excavation rate of 30 m (100 ft.) per working day. The tunnel diameter was much larger than was needed for site characterization and led to several problems and inefficiencies. Excavating smaller tunnels is preferable for future site investigations for several reasons (NWTRB 1993: 16). Smaller-diameter tunnels are more stable structurally, particularly when excavating in fault zones and rock of low quality. They could allow eliminating some or all ground support. They also would be less expensive to maintain. A smaller TBM is more efficient and more cost-effective because a smaller-diameter TBM advances faster through rock. Construction risks, delays, and expense also increase with increased tunnel size. More time is required to install additional rock support where needed and more frequent TBM maintenance is needed because of larger, less reliable components and more frequent cutter changes. In addition, because DOE planned to incorporate the ESF into the repository, costly and time-consuming quality-assurance procedures that would be unnecessary for a site-characterization construction project were required. A possibly overriding, although nontechnical, reason for not using tunnel diameters larger than necessary for site characterization might be to avoid any appearance of prebuilding the repository.

Future repository developers should carefully consider (1) the size of tunnels needed for site characterization; (2) the use of off-the-shelf excavating equipment when possible; and (3) obtaining assistance from geoengineering experts early in the decision-making process.

3.4. ENGINEERING AND PROTOTYPING

Engineering Program

DOE initially viewed the Yucca Mountain program primarily as a science program with a straightforward objective: gather and analyze sufficient information to determine whether Yucca Mountain is a suitable site for a deep geologic repository. Although there were many positive early indicators that geologic disposal in a thick unsaturated zone in the arid Southwest would be satisfactory (e.g., Winograd 1974; Roseboom 1983), there was insufficient information to be certain. Information was gathered and analyzed, and, at some point, DOE determined that the site was suitable.[25]

At that point, what had been a science program became an engineering program. That did not mean that the need for science vanished or even decreased. In fact, science continued to have an important role in providing information for design and for the TSPA-LA, a critical element of the license application. Rather, it meant that the objective of the Yucca Mountain program had changed. No longer was the objective to determine site suitability and thus whether the Secretary of Energy should take the formal step required by Section 114 of the NWPA of submitting a recommendation to the President that the President approve Yucca Mountain as a site for repository development. Now the objective was to do what was necessary to design, license, build, and operate a repository at Yucca Mountain within the framework of the U.S. waste-management system.

In the context of a long-term repository, the term "engineering program" means a large, complex project that involves siting, design, permitting, licensing, construction, and operation; that lasts many years; and that requires a substantial amount of science and technology, some of which may be new. An engineering program first needs to be recognized as such, and then it needs to have a management and organizational structure that can integrate all aspects of the project, including public information, scientific studies, site characterization, engineering development and testing, design, procurement, construction, operation, and closure with an overall view of the whole system. Continuity of managerial and technical leadership, consistent funding, and the right incentive structure for completing the work are essential pieces and parts of the successful structure. Many scientific investigations may be needed to support the program, but management cannot lose sight of the fact that the science is there to support the needs of the engineering program.

The *design* of a deep geologic repository at Yucca Mountain was, by its very nature, an engineering problem of the first order. It had a clear objective, involved numerous constraints, presented unprecedented challenges, and required many choices to be made—

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[25] Pinpointing exactly when DOE made that determination is difficult, but it came well before the formal determination by the President and Congress in 2002.

all hallmarks of a classic engineering design problem. However, this was a design problem the likes of which humanity had never before attempted, because it involved a time scale that required predictions of material and system behavior tens and hundreds of thousands of years into the future. Some perspective on the uniqueness of this temporal projection comes from the realization that the most ancient monuments of past engineering achievement, such as Stonehenge and the Pyramids, are barely five thousand years old.

The approach to any engineering problem takes advantage of experience and scientific knowledge. In the case of a repository in Yucca Mountain, at the outset there was little direct repository-engineering experience, and the available scientific knowledge had significant gaps. Natural analogs can provide some insight and guidance for making design decisions, but such "found experiments" are rare and their lessons are limited by the very fact that they are analogs rather than models. There was, of course, experience in relevant technologies, such as mining operations, and knowledge of basic scientific principles, such as subsurface hydrology, but this experience and knowledge had to be adapted to the new conditions, constraints, and challenges of the unprecedented problem of a repository.

Engineers are used to working with a paucity of experience, and they have demonstrated time and again that new challenges can be met. The Manhattan Project and the Apollo Program are two outstanding examples of first-of-a-kind challenges to engineers. The two programs were unique in the need for collaboration between engineers and scientists. The Manhattan Project launched nuclear energy, and the Apollo Program was the outstanding early accomplishment of human space flight. The naval nuclear propulsion program provides a similar story of a successful engineering program. It seemed to the Board that DOE was not exhibiting the same commitment to the engineering-development process in the Yucca Mountain program.

Gaps in scientific knowledge often can be filled by the results of research programs, and this was what the Yucca Mountain program seemed to focus upon. Even after site suitability had been established, many open questions remained about such phenomena as the movement of water in the unsaturated zone and the corrosion of metals in an oxidizing environment, and the questions presented relatively well-defined engineering-scientific problems about which researchers could hypothesize, devise experiments, collect data, and present results. Because the areas of research were unexplored, the work produced new knowledge. The new knowledge clearly benefited the models used in the probabilistic risk assessments that were a principal part of the license application.

Science and the preparation of a license application, including probabilistic risk assessments, tended to overshadow the design aspects of the Yucca Mountain program, which continued to be a neglected area. When public presentations were made on the design of surface facilities, for example, their content often lacked detail. It became increasingly obvious that the engineering aspects of the program were subordinate to the scientific and license considerations. When questions were raised about prototyping and demonstration programs, they were dismissed as less important because the equipment involved was commonly used in mines and other analogous operations. This may well have been the case for the invert, but the application of the equipment for emplacing drip-shield sections, for example, was as unique as the drip shield itself and should have been the subject of a well-considered prototyping program culminating in a full-scale demonstration that the tasks could indeed be carried out successfully. In a recent presentation to the Board, a seasoned mining engineer pointed out the uniqueness of the drip shield and the drip-shield emplacement device, as well as the difficult conditions for drip-shield emplacement (Kendorski 2005).

Although DOE began transitioning from a science program to an engineering program in the late 1990s, engineering did not seem to arrive at its proper place in the Yucca Mountain program until about mid-2006, when DOE management acknowledged that engineering should be driving the program. That led to the completion and submittal of the long-overdue license application to the Nuclear Regulatory Commission. However, with the subsequent decision by the Administration to terminate the Yucca Mountain program, deep geologic disposal activities have been relegated to a small, generic science program in DOE's Office of Nuclear Energy, pending recommendations from the Blue Ribbon Commission on America's Nuclear Future and subsequent action by Administration and congressional policy-makers.

Among the principal lessons learned from the Yucca Mountain program should be that an engineering program should from the outset be recognized as such and be managed and operated accordingly. This means that it should be viewed not so much as a research and development program but rather as a development and research program, with the engineering goal of developing the final design for a repository being foremost.

The ultimate design and operation of the system always should motivate the objectives of the appropriate scientific research and expect them to be in service to the engineering objectives. The aerospace engineer Simon Ostrach has described such prioritizing as Research for Development (R4D), with the design objective in the driver's seat (Ostrach 2008). Admiral Rickover's nuclear naval propulsion program was an excellent example of the success of this philosophy.

Another lesson is that of the need for continuity of management, personnel, and funding. Contractors came and went, and managers cycled in and out, while the amount of money available in the next fiscal year was always in doubt and not under the control of the *management of the program. Any engineering program would benefit greatly from having a dedicated organization that would maintain continuity of its personnel, especially of its management and principal engineers and scientists.*

Prototyping

The French, whose success in the development and use of nuclear power is well known, have done significant prototype testing of the engineered systems they plan to use in relation to waste disposal. When the Board visited nuclear development sites in France in 2008, the French commitment to prototype testing was clear. Not only would such testing serve to give the public confidence in the approach being used but it also would provide a firm basis for the French license application.

Similarly, Svensk Kärnbränslehantering AB (SKB), the utility-owned company responsible for the Swedish waste-management and repository programs, has had prototype programs under way for many years for the waste package, for the equipment used to weld the lid onto a loaded waste package, and for the equipment used to emplace the waste packages in the repository, as well as other novel equipment items. As in the French program, these prototype efforts build public confidence, help explain the program, and provide valuable information for a license application. Tangible, working items at or near scale that can be observed and discussed help build public confidence (Coleman 2010). Several Board members visited the Swedish and Finnish repository programs in 2006. Sweden and Finland cooperate closely in repository development because they plan to dispose of high-activity waste in similar geologic media using the same repository design.

Prototyping and testing of engineered systems are necessary to enhance confidence in their feasibility and to adjust designs. Any engineered barrier system is likely to have unique design features that are important for performance and that therefore need to be confirmed. For example, in the Yucca Mountain design, the drip shield, the waste package, and the pallet were in this category. In addition, equipment designed to emplace the drip shield and waste package and the equipment used to make and examine the final closure welds of the waste package also need confirmation.

To its credit, DOE began work on planning its prototype program in the mid-1990s, which put the program on a fast track when site suitability was determined. However, the only aspects of a prototype program that were implemented were the waste package and the equipment for welding the double lids onto a loaded waste package, and these aspects were only partially implemented. For example, at one time, nine full-scale waste package prototypes were part of the planned waste package prototype program. Yet, the waste package prototype program built only one full-scale waste package and several full-scale waste package sections. The information gained was invaluable and affected the final waste package design. Early prototyping also demonstrated the impracticality of shrinkfitting the two cylinders of the waste package together, so an early design that called for shrinkfitting was rejected. Prototyping also exposed some issues in heat-treating the waste packages and in the design of the weld grooves. The system for welding and inspecting the final closure lids onto the waste package was developed at full scale by Idaho National Laboratory personnel and demonstrated at full scale in Idaho Falls, Idaho. It was a success, although only one full lid weld was performed.

At least the waste package prototype program and the final closure weld system produced some results. DOE had prototype programs on the books for the drip shield, the pallet, the invert, and the drip-shield emplacement equipment, but these programs never began. This is a particularly significant omission for the drip shield and the drip-shield emplacement equipment because TSPA calculations indicate that drip shields are important for repository performance, at least with respect to the models implemented and their assumptions. If the prototype programs for the drip shield and its emplacement equipment had been implemented, the information obtained may have been useful in the licensing process.

Another obvious candidate for prototyping was the TAD canister. DOE issued two contracts for designing and building a TAD canister. The contracts both produced designs, but the contracts were terminated without fabricating prototype TAD canisters.

Future repository programs should include the development of prototypes of novel equipment items, such as the waste package, the platform that the waste package rests on, any novel instrumentation, and any novel equipment used to emplace, move, or install other equipment items.

Drift Degradation During the Preclosure Period

Drifts normally degrade over time because of rockfall, flaking, dust, seepage, seismic events, and other natural phenomena. This degradation process likely would deposit debris on the invert, the rails, and the emplaced waste packages. The debris could obstruct the movement of waste packages into the drifts, a process DOE intended to accomplish remotely using emplacement vehicles. Clearing obstructions would be challenging because it also would be done remotely because of the high-radiation environment. DOE assumed that there would be no drift degradation at Yucca Mountain during the 50- to 300-year preclosure period. DOE also had confidence that the emplacement-drift ground support system would function effectively. The technical basis for DOE's confidence was not apparent. Further, DOE had not developed contingency plans for cleaning and removing debris from the invert and the rails before emplacement of the drip shields. *Future programs should take potential preclosure drift degradation into account, particularly if the preclosure period is long.*

Future repository programs should systematically evaluate the likelihood and consequences of drift degradation during the preclosure period and, if necessary, design appropriate measures for preventing such degradation or mitigating its effect. Future programs also should consider developing plans for cleaning and removing debris.

3.5. INTEGRATED TOTAL WASTE-MANAGEMENT SYSTEM

Transportation-Aging-Disposal Canister

The NWPA requires DOE to provide transportation casks and other equipment needed for transporting SNF from commercial nuclear power plant sites to a repository site. Beginning in the mid-1980s, DOE undertook the Cask System Development Program (CSDP) and contracted with cask manufacturers to design transportation casks of four sizes for transporting SNF from utility sites. The casks in the CSDP were being developed to transport bare fuel without any internal canister. Before work on the CSDP was completed, however, it was largely superseded by the Multipurpose Canister (MPC) program. In the MPC program, multiple SNF assemblies would be contained in sealed thin-wall metal canisters that would be placed in a range of casks for storage and transportation. The MPC program was terminated by congressional action in 1996.

DOE's most recent canister-design program was identical in concept to the MPC program. In the new program, multiple commercial SNF assemblies would be placed in TAD canisters at utility sites, and the canisters would be placed in a storage cask, a transportation cask, or a disposal cask (waste package), depending on the next function for the loaded canister. Movement of the SNF from one function to the next would simply be by moving the loaded canister from one cask to another. Work on the TAD canister program began in 2005 (DOE 2007) but was halted in 2009, following initial actions by DOE to terminate the Yucca Mountain program. The TAD canister program and the previous MPC program were significant steps forward in recognizing the benefit of preventing repetitive handing of bare fuel. The programs also introduced the concept of standardizing container designs, with the attendant economies in package fabrication, loading, and subsequent handling operations. Unfortunately, because these concepts were not successfully introduced in the program earlier, there already is a large and growing quantity of SNF in storage at utility sites in a wide and widening range of container types.

Two additional aspects of not introducing the TAD canister earlier in the program could have proved problematic. By the time the TAD canister concept was introduced, waste-package designs had been fixed and much of the conceptual design of the surface facilities at the Yucca Mountain site had been completed, which limited the maximum size of a TAD canister. Many reactor sites could accommodate a larger canister, however, and, in fact, are using MPC-like dual-purpose (storage and transportation) canisters that are larger than the largest TAD canister permitted by the Yucca Mountain program. In addition, DOE specified the capacity of the TAD canisters and the maximum length of the spent fuel that TAD canisters would be expected to accommodate. This resulted in a TAD canister design that cannot accept some SNF, such as the SNF assemblies from South Texas Project reactors, which are longer than the fuel used in other U.S. PWRs (~14 ft vs. ~12 ft). Future reactors also could use this longer fuel. *Future programs should consider the TAD canister concept carefully because of its potential safety, handling, system-simplification, and cost advantages. However, the programs should ensure that the sizes of the canisters are compatible with fuel dimensions and the sizes of dual-purpose canisters.*

Nuclear utilities are moving increasingly to dry-storage systems. For most dry-storage systems, the SNF is sealed into large metal dual-purpose canisters, and the canisters are placed in massive shielded casks or structures. As mentioned, many dual-purpose canisters already are too large for the repository design in the license application submitted to the Nuclear Regulatory Commission by DOE, and the trend is toward larger canisters. Other canister issues also exist. For example, the nuclear criticality regulations for canisters (either 10 CFR 63, which applies to Yucca Mountain, or 10 CFR 60, which applies to other repositories) have not been tested through an entire licensing process. Thus, not known is whether the dual-purpose canisters that already are loaded or will be loaded in the future would meet the criticality requirements of the disposal regulations, especially for long-aged and high-burnup SNF. Certainly, however, the Nuclear Regulatory Commission would have to allow burnup credit for both actinide depletion and fission products for there to be any chance that dual-purpose canisters loaded with SNF could meet repository regulatory requirements. DOE worked on the burnup credit issue for at least 15 years in the Yucca Mountain program, although the degree of management priority accorded to the issue varied widely. Because the burnup credit issue applies to any repository, *DOE should continue to vigorously pursue the burnup credit issue because it is important to storage, transportation, and disposal of SNF.*

The experience with TAD canisters and the fact that current dual-purpose canisters are too large for the Yucca Mountain design in the license application argue strongly for *addressing the entire waste-management system from at-reactor to final disposal as a whole at the earliest possible stage of any new program.*

Future waste-management programs could benefit from any action that can be taken now, or in the near term, to specify requirements for SNF package designs to utilities and cask vendors. This would be in the overall interests of the program because it would prevent continuing the loading of a wide range of container and cask types, which may result in a requirement for repackaging before transportation of the containers and casks from the reactor sites or following transportation to a repository. This is especially important for the utilities whose reactors will reach their final shutdown date before the implementation of a disposal program for SNF from commercial nuclear power plant sites.

Transportation

As noted earlier, the TAD canister concept had the advantage of minimizing the handling of SNF. However, there are transportation issues involving TAD canisters.

Loading of TAD canisters at a commercial reactor site would require a handling system with a minimum 100-ton lifting capacity. The current equipment configurations at many sites would not meet this threshold (TriVis 2005). Each of those sites would require an upgrade to its cranes' lifting capacity, incurring significant expense and possibly creating operational downtime. At some facilities, the extent of the required upgrading could be cost-prohibitive, requiring other operations to be arranged, possibly including transportation of SNF from the facility for loading into TAD canisters at another location.

At many sites, short-line (locally and regionally owned) railroads likely would have been relied on for transporting TAD canisters and their overpacks to transfer points, where the short-line railroads would connect with the mainline railroad network (DOE 2008a). Many of these short-line railroads would require significant upgrades to meet DOE's minimum track-quality standards. If these short-line railroads could not be upgraded—perhaps because of the expense involved—other, more logistically complicated, modes would have had to be used.

Perhaps the major transportation issue, however, was the lack of connection of the Yucca Mountain site to the national railroad infrastructure. Making the connection would have required construction of a new 330-mile line from the Caliente, Nevada, mainline railhead to Yucca Mountain at an estimated cost of approximately $3 billion (DOE 2008b). Significant delays in constructing the new line would have reduced the efficiency of the repository construction project, delayed the start of repository operations, and potentially changed the characteristics of the waste stream arriving at the repository. If the new line were never constructed, the feasibility of the entire Yucca Mountain program would have been at risk. No contingency plan appeared to have been developed to address the possibility that the new line might not be built (NWTRB 2004; NWTRB 2006).

In its surface-facility design and in its throughput analysis of the Yucca Mountain receipt facility, DOE assumed that 90 percent of the commercial SNF would arrive at the repository site packaged in TAD canisters, although this assumption was acknowledged to be questionable. The 10 percent of the commercial SNF not packaged in TADs would be received at the waste-handling facility (WHF) on the repository site, where the fuel assemblies would be transferred to TAD canisters. However, the WHF was designed with limited capacity, and if more than 10 percent of the commercial SNF did not arrive in TAD canisters, backlogs would have been created, forcing additional amounts of commercial SNF to be placed on storage pads. Alternatively, there would have been a need to construct additional WHFs.

This requirement for repackaging uncanistered SNF into TAD canisters at the repository site may not, at first sight, appear to be an issue that has a particular bearing on the requirements of the transportation system. Any difference between the quantities of SNF assumed to be loaded in TAD canisters at the nuclear power plant sites and what might happen in practice would change the numbers and types of casks needed for fuel storage, as well as the requirement for cask-handling equipment, maintenance, and other issues, such as the logistics of the transportation program. This underscores the requirement for recognizing the interdependencies of the design of the fuel cycle and the program for transporting high-activity waste.

The research and development plan developed by DOE's Office of Nuclear Energy appears to take the Yucca Mountain experience into account and to recognize the significance of the transportation function as an important and integrated component of any system design that emerges (Schwab 2010).

Integration of the Total Waste Management System

Despite the fact that the Yucca Mountain program is a total system consisting of waste acceptance, transportation, handling and repackaging, emplacement, and eventual closure and monitoring, there was little evidence of efforts to manage it as a total system until the early 2000s. By then, a complicating factor had entered the equation: Utilities began to sue DOE for nonperformance under the Standard Contract (10 CFR 961), and DOE would not talk with utilities outside the courtroom, complicating understanding of characteristics of the front end of the total system. Also complicating management of the program as a total system was the organizational scheme chosen. Scientists and engineers stationed in Las Vegas, at National Laboratories, or at the USGS offices in Denver were focused on the repository. The responsibility for waste acceptance and national transportation was located in Washington, D.C., and the majority of the people supporting those activities were located there. Headquarters for OCRWM also was located in Washington, but the majority of OCRWM employees were in Las Vegas. During the 1990s and before, scientists were splintered into many independent groups by discipline and by their locations—many of which were hundreds of miles from program offices in Las Vegas. Communication among scientists, engineers working on the repository design, and analysts working on performance assessments did not result in effective coordination. Despite the fact that waste management and disposal is a total system, it was not being recognized and treated as one.

Regardless of the institutional form selected for future repository programs, they are likely to face the same issues of communication and coordination among scientists, engineers, and performance-assessment analysts. Handling and transportation of the waste need to be resolved in a timely manner to ensure that schedules are met for testing, startup, and successful operations. For the Yucca Mountain program, there was little evidence that such activities were effectively integrated into the overall program plan, particularly in relation to the program schedule.

Ultimately, the success of the Yucca Mountain repository as a total system would have depended on the smooth integration of its transportation, surface facility, and emplacement operations. There were computer simulations of the integrated system, but, except in a notional sense, they did not and could not incorporate the real-world complications of system and machinery bottlenecks and breakdowns, not to mention downright inoperability for reasons revealed only in a full-scale or near-full-scale pilot plant. As a result, the design and functionality of the repository surface facilities were not well integrated with the balance of the waste-management system. Information was lacking on a comprehensive integrated throughput model for the surface facilities with time steps compatible with the task durations. The assumptions that input for each facility would be available when needed and that output would be removed when processing is complete do not represent a realistic situation, nor was any justification for the assumption of an availability[26] of 75 percent provided. Too few operational details were presented to the Board to obtain an understanding of the various operations and how they interacted, especially during upset conditions. Future programs must take integration of the entire system into account.

Managing High-Burnup Spent Fuel

Before 2000, most fuel discharged from nuclear power plants in the United States had burnups below 45 GWd/MTU, which is considered the threshold for high burnup. SNF burnups of 45-50 GWd/MTU are typical currently, and burnups of over 60 GWd/MTU are expected to be routine in the future. Consequently, although there is considerable experience with storage of low- to moderate-burnup SNF, both in reactor pools and at dry-storage facilities, there is little experience with storing high-burnup SNF, the likely dominant SNF form requiring future storage.

In parallel with the trend to higher burnups, the likely storage period for SNF before processing or disposal has been increasing, with storage periods of 100 years or more now foreseen. The termination of Yucca Mountain is one of the principal reasons for this increase. Although the performance in the reactor of fuels designed for higher burnups is established, the effect on fuel integrity of storage over such long periods and the subsequent behavior of that fuel in handling or transportation is not known, particularly for high-burnup SNF.

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[26] Availability is the time that a structure, system, or component is capable of performing its intended function as a fraction of the total time that the intended function may be demanded (NEI 2007).

Under the current U.S. regulatory framework, a safety basis has been demonstrated by licensees for dry storage of SNF for 60 years. A safety basis has not been developed, however, beyond this period of time. Of particular concern are the potential effect of long-term aging on SNF and the degradation of storage-system structures and components, both of which have implications for cladding integrity, criticality safety, and offsite radiation dose in both normal and off-normal conditions. Complicating matters is the fact that the dry-storage systems have varying contents, designs, and applications, as well as being located at different facilities with different environments. Consequently, there is not yet adequate experience to give the necessary assurance that SNF and the storage canisters in which it is loaded will be in a suitable condition for future transport operations after extended storage periods. Moreover, the extent to which the fuel may need to be repackaged before transport also is not known.

DOE, the Nuclear Regulatory Commission, and the nuclear industry have recognized the need to approach high-burnup considerations as an integrated system involving interdependencies among storage, transportation, disposal operations and, potentially, reprocessing. The goal of this effort is to take these considerations into account as new fuel designs and transport packages are developed.

There is another issue that has not yet become a focus of the nuclear industry, although there is an increasing realization that it must be addressed. Although the performance of advanced fuel designs in the reactor is well-established, the need to extend the periods during which SNF will require storage means that it is important also to take this into account in the design of new fuel types. A small penalty in fuel performance in the reactor resulting in a major advantage during the storage, transport, and disposal of SNF could have significant overall economic benefit for the nuclear power plant operator; these sorts of trade-offs warrant detailed assessment. These developments, both individually and collectively, offer opportunities for fully recognizing interdependencies in the transportation waste-management system as part of the system design process.

3.6. PERFORMANCE ASSESSMENT AND INTEGRATION

Performance Assessment

Given the enormous problem complexity and inherent uncertainties, probabilistic modeling and simulation is the only viable way to predict quantitatively the long-term performance of a geologic repository such as Yucca Mountain. The well-established discipline of probabilistic risk assessment (PRA) provides the necessary methodological framework, modeling principles, and tools for this purpose. PRA is of particular value when the likelihood of possible future states of the physical system and governing phenomena are poorly known and are best described by discrete or continuous alternative scenarios. In that case, PRA provides a probabilistic framework that couples the scenarios with deterministic representations of the underlying system and processes. The probabilistic model used by the Yucca Mountain program is known as Total System Performance Assessment, or TSPA. DOE developed numerous iterations of TSPA in the course of its investigations of Yucca Mountain. The first iterations were rudimentary, although the most recent iteration, known as TSPA-LA (license application), was the most sophisticated. TSPA-LA represented the culmination of the most thorough study of the performance of a geologic repository for high-activity waste ever performed by U.S. scientists and engineers.[27]

Although TSPA-LA deviated from some of the more-accepted PRA practices in modeling risk scenarios and in final representation of risk metrics, as discussed later in "Measuring and Portraying Risk," it relied heavily on PRA technology and also offered several methodological innovations and advancements.[28]

The major components of TSPA-LA included models of the waste; the engineered barrier system, including waste package and drip shield; the natural barrier system, including the hydrogeologic unsaturated and saturated zones; and the biosphere. Scenarios considered included the nominal scenario, earlier-than-predicted failure of engineered barriers, and seismic and igneous events. The events that were included had an estimated frequency of occurrence equal to or greater than 0.0001 per year for 10,000 years (or 1 in 100 million). The period of analysis, generally on the order of 20,000 years in TSPAs produced before 2004, was extended to 1,000,000 years in TSPA-LA.

TSPA provided a quantitative estimate of *expected* (probability weighted) radiological dose to humans associated with a geologic repository at Yucca Mountain. This quantitative measure was based on estimates of the *likelihood* of events and processes leading to exposure, and on the *consequences* of those events (in terms of dose to the human population). Uncertainties associated with models and input parameters were estimated and propagated through the entire TSPA model to obtain an uncertainty distribution of the expected dose. Advanced statistical techniques were used to identify the relative effect and significance of individual repository characteristics in the TSPA calculations. Results of those analyses were valuable for identifying fruitful areas for further investigation and risk reduction.

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[27] TSPA-LA undoubtedly was informed by and benefited from experience gained from previous performance assessments of other complex projects, particularly the performance assessment developed to obtain compliance certification for WIPP (DOE 1996). In fact, many of the scientists and engineers who participated in developing TSPA-LA also had been involved in developing the WIPP performance assessment.

[28] A major issue with TSPA-LA as a performance assessment is its strong orientation toward a regulatory-compliance case. This manifests itself in sometimes excessive and unrealistic use of *conservative bounding analyses* that limit understanding of the true performance of the system. Risk analysis, on the other hand, aims at providing the most realistic assessment of performance on the basis of the current state of knowledge, accounting for knowledge gaps and other sources of uncertainly with probability distributions. If done correctly and consistently, the compliance case could be a natural byproduct of the risk analysis.

TSPA was used to estimate the contribution to repository waste-isolation performance from each of the barriers (engineered and natural) over time. TSPA provided the capability to identify the particular radionuclides that contributed the most to risk.[29] Because of radioactive decay, the dominant risk-contributing radionuclides vary by time and by scenario. TSPA demonstrated that probabilistic dynamic modeling of large, complex natural and engineered systems can be performed. Output from a "Simplified TSPA" (SNL 2008f) developed late in the Yucca Mountain program was broadly consistent with the full TSPA and helped to improve confidence in the conceptual basis of the TSPA. Conceptual and numerical models of unsaturated fluid flow and radionuclide transport in fractured unsaturated rocks advanced as a result of Yucca Mountain studies. Many improvements were made as the models evolved with respect to computational tools, conceptualization of the host-rock physical properties, and improvements in conceptualization and representation of the transport of heat and mass in the waste-package environment. These models, sometimes abstracted to save computer time, were incorporated into TSPA.

Advancements in the state of the art in relation to the development of TSPA-LA provide many analytical and computational foundations that can be used in future studies of geologic repositories. In the area of characterizing and assessing uncertainty, TSPA-LA pushed the state of the art to higher levels, including (in selected cases) explicit treatment of uncertainties associated with models and abstractions, assessment and propagation of parametric uncertainties,[30] and separation of uncertainty resulting from the natural variability of physical phenomena (aleatory uncertainty) and knowledge-based uncertainty (epistemic uncertainty). Separation of sources of uncertainty provides the opportunity to identify knowledge gaps that are potentially significant in a risk-informed decision-making framework.

The bounding analyses of the TSPA-LA were important to managing the scope of the assessment and demonstrating compliance with dose standards. The Yucca Mountain program conducted multiple sensitivity studies using the full TSPA-LA and used a simplified TSPA to explore the effect of variations on some key assumptions and parameters. The objective of one such study, performance margin analysis, discussed later, was to develop a more realistic assessment of key processes and variables and related site performance than embodied in the "compliance model" TSPA-LA with its inherent *conservatisms* in the face of knowledge gaps and data limitations. Some limitations of this study are discussed later in this section.

[29] Besides its utility for a Yucca Mountain repository, such information would be extremely valuable in possibly influencing the future consideration of chemical separation of radionuclides to benefit repository designs.

[30] The TSPA lacked total consistency in this area, however. In some cases, single values rather than uncertainty distributions were used; in other cases, probability-based distributions were used but without supporting data.

The strength of an integrated model such as TSPA-LA is that the merits of the methods used and results obtained can be evaluated and debated by the informed scientific and technical community, as well as by regulators. In fact, an international group of experts assembled to review the version of TSPA performed before TSPA-LA concluded that this assessment represented a competent modeling effort in keeping with international practice (IRT 2002). Two general and 27 specific recommendations were made to improve the assessment. DOE addressed all of the recommendations and documented their disposition in an appendix to TSPA-LA (SNL 2008c). A later expert review also was conducted (BSC 2006). The performance assessment, although not perfect, was nevertheless a first-of-a-kind and provided a benchmark for future studies. It had the capacity for continuing to evolve and improve by capturing and embodying the latest advances in scientific understanding and engineering practice.

Enactment of the Energy Policy Act of 1992, P.L. 102-486, started the process by which regulations and standards for high-activity waste repositories became bifurcated in the United States. The United States now finds itself in the situation of having two sets of repository regulations and standards. One set, 10 CFR 63, 10 CFR 963, and 40 CFR 197, applies only to Yucca Mountain; the other set, 10 CFR 60, 10 CFR 960, and 40 CFR 191, applies to all other U.S. repositories. The set applying to other repositories has been essentially stagnant since the early 1990s. The set applying to Yucca Mountain has been shaped by extensive study, rule-making processes, hearings, and judicial decisions that have taken place since passage of the Energy Policy Act of 1992, and to some extent are still taking place today. As a result, the two sets of regulations and standards have many significant technical differences.

From a performance assessment point of view, an important difference is that the Yucca Mountain regulation (10 CFR 63) allows and requires that the performance of the total repository system taken as a whole be used to determine whether the site is acceptable and whether the repository meets the dose criteria specified in the regulation. Although the regulation (10 CFR 60) applying to other U.S. repositories allows performance assessment to be used, it also contains distinct criteria for various subsystems of a repository.

Any new repository program will require a regulatory framework for its site selection, characterization, and subsequent activities. That framework exists but it is dated and has not benefited by advancements made in almost two decades. Repository developers must anticipate that the framework may change. *The Board believes that the use of total system performance assessment should be required in the regulatory framework.*

Measuring and Portraying Risk

In part because PRA is now a well-established and demonstrated methodology (Garrick 2008), there is a definite trend toward using risk-based approaches to making decisions about high-hazard activities. To ease the transition from traditional (i.e., deterministic and prescriptive) methods of safety analysis and attendant rules and regulations and its legacy comfort zone, the Nuclear Regulatory Commission has adopted the concept of being risk-informed, rather than committing outright to risk-based decisions. Risk-based decision-making is particularly important for nuclear waste management and disposal because of the long time constants, the inherent complexities of understanding the health effects of radiation, and the wide range of alternatives to be compared.

Risk assessment for nuclear waste activities presents two problems. One is the credibility of the risk measure, and the other is the ability to fully understand its meaning. What seems to be lacking in many performance studies of high-activity waste disposal or storage sites, including the proposed Yucca Mountain repository, is a scientific statement of the actual *risk* involved. Risk is not quantified for the Yucca Mountain repository because TSPA-LA does not answer the question, "What is the risk?" Instead, it answers the compliance question of whether DOE believes that the regulatory *dose* standard established for the repository has been met. A dose standard is at least once removed from a risk standard (Moeller 2008, 2009).

The nuclear waste community would do well to follow the example of the U.S. commercial nuclear power industry and perform and continuously maintain and update PRAs. PRAs have become more visible in managing nuclear plant risk than have the federal regulations (Garrick and Christie 2002). That is because PRAs are much more meaningful and to the point because of their quantification of not only the risk but also the rank order of the contributors to risk. Another aspect of this issue that the nuclear waste community should follow to improve the transparency of its calculations is to calculate and display the risk of different dose levels (probabilities versus different dose levels) in addition to the less transparent measure of "probability weighted doses." This should be easy to do because the numbers are the same but how they are displayed is different. This is not to suggest that the current dose standard is unacceptable, but only to note that answering the question, "What is the risk?" should be part of the process because it provides much more information. Furthermore, such a practice would point the way to the possible next step in the evolution of a risk standard, if the regulators decide to do so in their quest for becoming more risk-informed.

Integration

In addition to its principal function of providing estimates of postclosure performance over very long periods of time, TSPA-LA served an important beneficial role as *technical integrator* of a vast store of knowledge and data describing repository characteristics.[31] A major scientific and computational challenge in assessing postclosure performance was and is modeling many dynamic and tightly coupled thermo-hydro-mechanical-chemical-radiological phenomena in a complex multivariate nonlinear system. Added to this complexity are varying degrees and types of uncertainty regarding the natural and engineered systems and knowledge gaps that had to be explicitly identified and quantitatively represented. TSPA-LA combined approximately 300 models and submodels from diverse scientific and engineering disciplines, combined with thousands of input parameters, to provide a model-based probabilistic assessment of the repository system's performance.

Documentation that demonstrates the acceptability of a repository to the public and policy-makers and the compliance of a repository to regulators is called the "safety case." It includes probabilistic risk assessments as well as corroborative information. Performance assessment is arguably the most important part of the safety case, but it also can and should have important functions during site characterization. Although DOE performed TSPAs early in the site characterization process, which the Board commends, its early use of performance assessment was largely independent of many key site-characterization activities. Performance assessment could have been used to help integrate the work between groups of scientists of different disciplines or from different organizations. For example, geochemists from one National Laboratory may perform site characterization to learn how the repository environment would evolve, while corrosion scientists from another National Laboratory may be conducting experiments to determine how various waste package materials would degrade in repository environments.

Thus, performance assessment models can help show the relationships between the work of the two disparate groups, as well as the sensitivity and relative importance of key environmental variables, e.g., temperature, pH, and corrosion rates. However, at least early in the Yucca Mountain program, performance assessment models and methodology were developed parallel with site-characterization activities rather than integral with them. *Future repository programs should use probabilistic performance assessments throughout the life of a program to help set priorities among site-characterization activities, i.e., to guide the research portfolio. If performance assessment shows that a particular variable or set of related variables is unimportant while showing that other variables are important, more management attention, funding, and manpower resources could be allocated to the latter set of variables.*

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[31] The TSPA-LA model and corresponding probabilistic simulation software were accompanied by a large volume of documents that described the technical basis for the diverse sets of models and data used and the computational methods applied.

Early performance assessments should be directed toward answering, "What is the risk?", rather than attempting to answer whether there is compliance with regulations. Regulations can change, and they did change during the course of the Yucca Mountain site-characterization and license-preparation phases. The measure of risk changes less, if at all. The parameter of "probability weighted dose" should be avoided because it is not transparent. The more transparent approach is to determine the probability of receiving a specific dose. Eventually, of course, performance assessment results must be cast in compliance-related terms. However, this is not necessary early in a repository project and may even be counterproductive for allocating resources or communicating with the public or policy-makers.

In the Yucca Mountain program, different analysis and design practices were used for different aspects of the waste-management and disposal system. For example, an entirely different approach to safety analysis was performed for the period after repository closure (postclosure) than for the period before repository closure (preclosure), making it very difficult, if not impossible, to optimize throughput and safety between preclosure and postclosure. The preclosure risk assessment was not an integrated probabilistic safety analysis, although the postclosure risk assessment contained most of the elements of a quantitative probabilistic risk assessment. For future repository-development activities, the Board recommends that a consistent framework of analysis and design be used for all elements of the nuclear waste-management and disposal system, including storing, accepting, handling, transporting, processing, emplacing, and aging of the waste and closing the repository. During the design of the surface facilities, it became apparent that despite the fact that they were only to operate for 100 or so years, their design requirements were based on events with very low probabilities of occurring in 100 years—resulting in overdesign. *The design basis for facilities should be consistent with their term of use.*

Waste forms may change, depending on how the future of nuclear energy evolves. The repository and its design should not be deterrents to changes in waste form that may come about as a result of more-advanced nuclear fuel cycles or recycling processes. This may not be an important issue in the first repository, if its waste capacity is approximately 100,000 MTHM or less, because of the current inventory and the known associated waste form. However, for future repositories, the compatibility of the repository and its design for different waste forms likely to exist for the duration of the repository should be assessed. Alternatively, if one assumes that the defense legacy waste goes to the first repository, subsequent ones may have a more homogeneous body of SNF of only a few generic types to deal with for such factors as heat loading, fuel-element dimensions, and transportation and handling requirements.

Performance Margin Analysis

Complex performance assessments may be necessary for licensing, but the public and policy-makers may not find them easy to understand. *The probabilistic performance assessment methods and results developed for Yucca Mountain are a state-of-the-art achievement and very valuable. They verge on being incomprehensible because of their complexity, however, except perhaps to organizations able to afford a large cadre of experts.* Future repository programs still may have to produce complex performance assessments for compliance purposes, but they also must produce more-realistic, less-complex performance assessments for nonregulators. As experience with the Yucca Mountain program clearly shows, not only the regulators decide the fate of a repository program. The audience for the safety case is much broader.

Reasonable conservatism is a valid approach to addressing questions of compliance with risk standards and limits on system performance. However, in complex and highly coupled systems, conservatism is not always easy to prove. An assumption that is apparently conservative in one context may prove to be nonconservative in a larger context. Some assumptions appeared not necessarily to be conservative, while others seemed unrealistically conservative.

Recognizing the many conservatisms in TSPA-LA, DOE also performed a "performance margin analysis" (PMA) (SNL 2008d) to evaluate the importance of many explicit and implicit conservatisms. The Board believes that performing the PMA was an excellent idea and should be repeated in future repository programs. However, the PMA did not go nearly far enough—a serious limitation that should not be repeated by future programs. Two examples of deficiencies in the PMA follow.

1. Despite the fact that zircaloy cladding is highly corrosion-resistant in the Yucca Mountain environmental conditions that are likely when water would contact the cladding, DOE conservatively claimed no credit for zircaloy cladding in TSPA-LA. The chief arguments for not taking credit were the uncertainty about the condition of the cladding after discharge from the reactor, particularly for high-burnup spent fuels, and the belief that taking credit for zircaloy cladding would not reduce dose estimates greatly in the first 20,000 years after closure (SNL 2007d: 3). DOE used PMA to examine how much taking credit for zircaloy cladding would reduce the estimated dose but limited its investigation to the first 20,000 years after repository closure. The analysis showed that the presence or absence of cladding would have little effect in the first 20,000 years. This is not surprising, because according to DOE analyses, very few waste packages would be likely to fail in the 20,000-year period following closure, and therefore any protection offered by cladding would not come into play. DOE should have tested the value of cladding credit either by simulating a long-enough period that

substantial numbers of waste packages would fail or by running separate "one-off" cases in which waste packages are assumed to all fail at one time, and then measuring the difference in risk versus time as a function of waste package failure time. Future repository programs where the EBS has an important function should do the same.

2. Questions such as, "How important is the waste package?" "How important is the drip shield?" and "How important is the unsaturated zone beneath the repository?" are obvious ones. The answers to such questions help in understanding how the various components of a proposed repository function together as well as the degree of defense-in-depth and barrier redundancy in the repository. Although DOE recognized the importance of such questions and carried out performance assessment studies a decade ago to address them, the PMA did not address them. Future repository programs should address these questions, e.g., by running one-off cases.

4. CONTRIBUTIONS FROM THE EXPERIENCES OF OTHER PROGRAMS

4.1. LEARNING FROM OTHER PROGRAMS

Other countries are placing an increasingly high priority on the long-term management and ultimate disposition of high-activity wastes from commercial nuclear power generation and from defense activities. A strong international consensus has emerged that deep geologic disposal is feasible and that it is the preferable mode of disposing of such wastes (Sowder 2010). A broad range of approaches toward siting and developing deep geologic repositories is being pursued by national programs. Each program takes into consideration the operational needs, geology, and socioeconomic circumstances that are specific to the country in which the repository would be located. As discussed in the following paragraphs, there are many technical differences among the programs and some significant similarities. The United States can learn from both.

4.2. DEEP GEOLOGIC REPOSITORY CONCEPTS

Many nations with nuclear power plants have active repository development programs. The geologic media in which they are developing repository concepts are discussed briefly below.

Crystalline rock is an inexact term used here to denote intrusive igneous and metamorphic rocks composed of well-defined contiguous mineral crystals. The mineralogy is variable. Examples are granite, gabbro, diorite, gneiss, and migmatite. Crystalline rock is being considered or investigated as a geologic medium for repository development by China, Finland, Japan, Korea, Spain, and Sweden.[32] Finland and Sweden have the most advanced programs, with projected dates to begin repository operations of 2020 and 2025, respectively (NWTRB 2009b). Both Finland and Sweden propose to load waste into copper waste packages and emplace the packages surrounded by bentonite buffer in holes bored into the host crystalline rock. Access drifts would be back-filled with a bentonite-sand mixture. Fracture-free crystalline rock has low permeability to the flow of water. However, crystalline

[32] Granite also has been considered a repository medium by Canada, France, Switzerland, and the United States. Another igneous rock, basalt, an extrusive volcanic rock that generally lacks extensive crystallization, was investigated as a potential repository host rock in the United States during the 1970s and 1980s. Basalt was of interest because it typically has low primary interconnected porosity and permeability. However fracture zones, rubble zones, the tops of basalt flows, and tubes in basalt flows all can have high permeability. Borehole studies in basalt at the Hanford site in Washington found very high temperatures and highly unstable stress regimes at depth. Both of these conditions would pose significant challenges to repository development in that particular geologic setting.

rock is commonly fractured in nature, and fractures may have high permeability. Moreover, mining operations typically create fractures around excavations.

Argillite is a compacted, fine-grained sedimentary rock that contains clay as a major constituent. France, Belgium, and Switzerland are considering argillaceous rock as the host rock for a potential repository. Argillaceous rock can have the following advantageous characteristics: large homogeneous deposits, low permeability, and a tendency for cavities or fractures to close via plastic flow (creep) or swelling. In addition, argillaceous rock can have high sorption capacity for some radionuclides. Argillites also tend to be reducing because of the presence of organic matter. Of the nations contemplating repositories in clay, France has the earliest planned date for beginning repository operations: 2025. Other countries considering repositories in clay either have not set a date for beginning operations or expect to begin operations in the 2040s or later.

Salt is a sedimentary rock formed by evaporation. Salt (chiefly halite) in domes or in bedded formations has been investigated intensively by Germany and the United States for its suitability to host repositories. Salt has low permeability. The geologic persistence of salt also indicates a lack of groundwater flow because the salt would have dissolved if there were flow through the system. In addition, like weakly indurated clays, salt slowly flows, or creeps, under lithostatic pressure to close any fractures or voids that may have been caused by construction or emplacement activities in the salt.

The Roles of the Engineered Barrier System and the Natural System

Since at least the late 1970s, approaches to the long-term management of high-activity waste have adopted a “systems view” (IRG 1978). What counts is the performance of the entire repository system regardless of how that performance was allocated among the various natural and engineered barriers. In some countries, such as Finland, Sweden, and possibly Canada and Japan, the engineered system is mostly responsible for isolating and containing the waste. In others, such as France, Belgium, and Switzerland, the bulk of the performance can be attributed to the clay natural barrier. Similarly, in Germany and at WIPP, the bulk of the performance is attributed to the salt natural barrier.

As discussed in subsection 3.1, at Yucca Mountain, the principal role of the natural system is to provide an environment in which the EBS can fulfill its role of delaying radionuclide release for a very long time and ensuring that release rates are low. Repositories in crystalline rock appear to have a similar relationship between the EBS and the natural system. However, designs of the EBS for the two most advanced repositories, those of Sweden and Finland, are much different from that of Yucca Mountain and rely on different mechanisms to accomplish their principal role. The Swedish and Finnish waste packages are made of copper, which is thermodynamically unable to corrode in dissolved-oxygen-free water.[33] In addition, the waste packages are surrounded by swelling clay. Over time, water that contacts the clay will cause it to swell, greatly retarding the flow of water to or from the waste packages.

The relationship between the EBS and the natural system is different for repositories in salt or weakly indurated clay, however. In these cases, the natural system assumes the principal safety burden because of its very low permeability and deformability. The EBS still has two important roles, however. One is to contain the waste while it is being transported into the repository, while the repository is still open, and while the waste is being transported out of the repository, if it is retrieved. The other is to compensate for excavation by plugging drifts, ramps, shafts, and holes to ensure that they are not fast pathways for radionuclide releases. Regardless of the geologic medium, therefore, the EBS is important.

4.3. TECHNICAL FACTORS AND APPROACHES COMMON TO MANY HIGH-ACTIVITY WASTE PROGRAMS

Experimental approaches at one site can result in beneficial transfer of knowledge to another site even for different geologic media. Following is a discussion of the technical experiences and approaches of different countries that may be transferable among waste disposal programs worldwide.

Underground Research Laboratories

Surface drilling can provide information on the extent, thickness, and lithology of strata that show promise for a deep geologic repository. Core samples can help determine the physical and chemical properties of the rock and the fluids it contains at a small scale, which permits further evaluation of the potential suitability of a site. However, core samples often do not preserve significant rock heterogeneities, including fractures and voids. Consequently, full evaluation of a site requires “getting underground” to confirm drilling results, to determine physical and chemical properties under in situ conditions, and to perform studies at or near full-scale and over longer distances or larger rock volumes than is feasible with drill holes. Engineers also can develop and test equipment and construction methods at or near full scale in underground research laboratories (URLs).

Countries that have or have had URLs include Belgium (clay), Canada (granite), Finland (crystalline rock), France (clay), Germany (salt), Japan (clay and granite), Sweden (granite), Switzerland (clay and granite), and the United States (granite, salt, tuff, basalt).

[33] That copper is thermodynamically unable to corrode in pure, dissolved-oxygen-free water is disputed by two researchers at the Swedish Royal Institute of Technology (SNCNW 2010).

Yucca Mountain's 5-mile Exploratory Studies Facility tunnel and 1.6-mile Enhanced Characterization of the Repository Block (ECRB) drift proved the value of getting underground for conducting scientific and engineering tests and measurements and for increasing confidence in repository performance estimates. The ECRB was especially important in improving fundamental understanding of the site because it allowed characterizations and studies in the area in which the waste would be emplaced.

The experience of other countries with URLs also reinforces the value of underground exploration. For example, German and French researchers carried out a large-scale thermal-hydraulic-mechanical heating test in the Opalinus clay at the Mont Terri URL in Switzerland (GRS 2007). The test was similar in many ways to heater tests conducted at Yucca Mountain (Tsang and Birkholzer 1997). Underground heater tests would have been infeasible without subsurface accessibility. Underground tests and experiments are necessary to understand interactions between the waste characteristics and the near-field geology disturbed first by construction and then by the heat generated by the waste.

Experimental work on the effects of temperature on salt has been carried out at WIPP in New Mexico (Munson 1990), the Asse salt mine in Germany (Rothfuchs 2004), and a salt mine in Lyons, Kansas (Buchanan 1989). Surface and underground exploration and characterization of salt were carried out at WIPP, at the Lyons salt mine, and at Gorleben in Germany. As with potential repository sites in tuff and clay, information gathered from boreholes can reveal whether a site is promising, but extensive underground exploration, characterization, and in situ experimentation are needed to evaluate the suitability of a site and to obtain the information necessary to model its short-term and long-term behavior. Underground work was coupled with aboveground laboratory studies carried out in the United States on waste form leaching and dissolution in brines and in Germany on corrosion of potential waste package materials in brines.

Several URLs in crystalline rock have operated over the years. Construction began on the Äspö Hard Rock Laboratory in Oskarshamn, Sweden, in 1990 to replace the underground laboratory at the Stripa mine (in central Sweden, about 150 km west of Stockholm). The Äspö Hard Rock Laboratory began operation in 1995 and continues to operate. The laboratory at the Stripa mine operated between 1976 and 1992. Construction of the ONKALO URL in Olkiluoto, Finland, began in 2004 and reached a final depth of 350 m in 2010. It succeeds the Olkiluoto Research Tunnel, which began operation in 1992. Other laboratories operating in granite are in Japan and Switzerland (Grimsel). Laboratories in granite no longer operating are in Canada (Whiteshell), France (Fanay-Augères), and the United States (Climax) (EDRAM 2008).

International cooperation at the Stripa, Whiteshell, and Grimsel laboratories was extensive. International cooperation at the Äspö Hard Rock Laboratory also has been extensive, involving many nations. Finland and Sweden are strongly motivated to cooperate because they share key features of repository design and site geology. The cooperation has resulted in sharing ideas, communicating results, and lowering research costs through shared funding and avoidance of unnecessary repetition. Future U.S. repository programs will benefit from cooperative international research, regardless of lithology.

Prototyping

The conceptual design for the repository in France includes many novel material and equipment items for containing or emplacing the waste. They include seals and plugs for shafts and access drifts and the machinery for placing the seals and plugs; the waste package itself; and the equipment for sealing the closure lid onto the waste package after the package is loaded with waste, for inserting the waste packages in their emplacement sleeves, and for placing backfill (a bentonite-based material) in the drifts used to access the waste-emplacement sleeves.

Because operation of the repository is only 15 years away, engineers at the French repository already have begun a prototype program. Full-scale equipment for pushing waste packages into the emplacement sleeve has been developed and is being tested. Clearly, all of the novel equipment items will need to be developed and tested before the repository begins operation. The French repository is being designed for disposing of vitrified waste.

The designs for the repositories in Finland and Sweden also have several novel engineered components for containing or emplacing the waste. They include the copper waste package used for direct disposal of spent fuel; equipment for sealing the closure lid onto the waste package after the package is loaded with spent fuel; machinery for transporting the packages underground and emplacing them; rings of compressed bentonite; and machinery for making and emplacing the bentonite rings.

An example of the extensive prototyping developed by the Swedish program was the design and manufacture of a solid copper container with a wall thickness of 50 mm. Engineers in the Swedish disposal program realized early that the lids would have to be attached to the waste package shell by welding to ensure long-term leak-tightness. Although methods existed to weld copper, making 50-mm-thick welds in copper was an unusual challenge. Accordingly, the Swedish nuclear-waste program management decided in the mid-1990s to build a full-scale prototyping facility to test, develop, and perfect welding methods for sealing waste packages. The facility, the Canister Laboratory, opened in 1998 in Oskarshamn, Sweden. The first welding method used was electron beam welding, an existing method but one that had not been used to make thick copper welds. At the laboratory, the method was used to join full-scale waste packages and lids. The method was developed successfully but required precise control of parameters for reproducible, acceptable welds. Nondestructive methods for examining weld quality were developed at the same time. In the 1990s, Swedish engineers also began working at the laboratory level with The Welding Institute in Cambridge, England, to develop an alternative method for sealing waste packages based on friction stir welding. Following its successful development, equipment for sealing waste packages at full scale by friction stir welding was installed at the Canister Laboratory, where it was perfected and then chosen in place of electron beam welding.

Over the same period, a full-scale shielded waste package deposition machine was designed, constructed, and deployed at depth in the Äspö Hard Rock Laboratory using full-scale waste packages filled with surrogate (nonradioactive) waste. In addition, engineers in the Swedish program developed full-scale equipment for manufacturing the bentonite rings that will be placed around emplaced waste packages, and they also carried out full-scale experiments for placing and handling the rings.

Each of these prototyping activities was critical for engendering confidence that successful emplacement and permanent disposal of nuclear waste generated by the Swedish reactor program could be accomplished. The Swedish program has set an excellent example of prototyping, one that the future U.S. program should emulate.

Thermal Management

High-activity waste generates heat as it decays, and the effect of that heat on the host rock must be determined. This requires knowledge of the thermo-physical properties of the rock as well as carefully developed and sophisticated mathematical models based on first principles of heat transfer. If changes in chemistry or mineralogy over the range of expected temperatures are potentially significant, then those processes must be included in the models. Thus, all repository programs limit the maximum temperature that the host rock will encounter. The limit can be met by aging the waste before emplacing it, placing waste packages farther apart, providing better heat transfer in the repository, or by other engineering means.

Temperature limits also must be set for clay-based buffers. Because a future U.S. repository could include clay formations or clay-based buffers, the U.S. program would benefit from understanding the thermal modeling of other programs, from examining the designs of other programs to achieve thermal management goals, and from learning the rationale behind the engineering approaches to achieving the thermal goals. If the host rock of a future U.S. repository is clay, the thermal modeling and management work of other clay programs would be directly useful.

Salt has a higher thermal conductivity than clay and may contain inclusions of brine that can migrate from regions of lower temperature to regions of higher temperature. In addition, the creep rate of salt increases with temperature. (The creep rate of clay depends in part on the degree of induration of the clay.) The effect of heat generated by the waste on the specific salt formation under consideration must be determined. Extensive thermal modeling of waste emplaced in salt has been performed in both Germany and the United States and is continuing in Germany. If salt is considered for a future U.S. repository program, approaches to thermal management in other salt programs should be monitored carefully.

Whatever host rock is chosen for a future U.S. repository, the thermal modeling and management work of the United States and other countries will be of value.

Reducing versus Oxidizing Environments

The proposed Yucca Mountain repository is the only one in which the repository bulk environment would be always oxidizing. This is due to continuous gas exchange with the atmosphere. The repositories of other programs also would have a period during which the environment would be oxidizing, but the period would be brief—a few hundred years or less—and would occur immediately after repository closure. The cause of the brief oxidizing period for repositories of other programs is the oxygen in the air left behind in drifts at the time of repository closure, oxygen entrapped during placement of buffer or backfill, atmospheric oxygen that had diffused into host-rock fractures during the repository preclosure period, and dissolved oxygen in porewater due to contact between the porewater and atmospheric oxygen during the preclosure period. The time required to consume the oxygen, e.g., by reaction with engineered components of the system or the geochemical environment, determines the duration of the oxidizing period. The environment becomes and remains reducing following consumption of the oxygen.

Although repositories in permanently oxidizing environments certainly are possible, emplacement of high-activity waste in reducing environments *generally* has three important advantages: (1) solubilities of most radionuclides are lower; (2) corrosion rates of metallic engineered components are slower and can approach zero; and (3) the UO_2 of spent fuel is stable in a reducing environment but converts to less-dense U_2O_3 in oxidizing environments. Because these advantages enhance long-term isolation of the waste from the human environment, future U.S. repository developers should ensure that repositories in reducing environments are considered.

Undisturbed in situ salt without brine pockets or significant impurities contains very little water, typically less than 1 percent (Roedder and Bassett 1980), and the water is salt-saturated brine. Water moves through the salt at slow rates because of the salt's low permeability. Brine can be highly corrosive.

As in repositories in clay or crystalline rock, the environment in salt repositories immediately after repository closure will be oxidizing. That oxygen would be consumed within a few hundred years after repository closure by reaction with iron-based structural materials and other materials. Because of the presence of metals, i.e., structural materials, the environment would become reducing following the consumption of free oxygen.

Use of Swelling Clay

Every repository program has investigated swelling clay (e.g., bentonite) as a major component of buffers, backfills, seals, or plugs. Buffers are packed around waste packages to retard radionuclide transport by slowing or stopping the flow of water to and from the packages and to provide mechanical support. Backfill is placed around the buffers or in access drifts when sections of a repository are being closed. Seals and plugs are used to prevent fluid flow through smaller openings.

Because swelling clay may play an important role in any future U.S. repository, future U.S. programs should include awareness of, and become involved in, cooperative international research efforts on buffers, backfills, and other uses of swelling clays.

Integrated Waste-Management Systems

The waste-management system in the United States is a highly complex system consisting now of waste acceptance, handling, transportation, and at-reactor storage. Eventually, the system also may include functions and facilities for repackaging, centralized storage, recycling, and final disposal. When fully developed, the U.S. waste-management system arguably will be the most complex because of the size and geographic dispersion of the nuclear power industry and the large amount of legacy waste requiring management and ultimate disposal. Today, however, other countries operate waste-management systems that are more complex, more complete, and more integrated than that of the United States.

France has been operating the most highly integrated, most advanced, and most complex national nuclear waste-management system in the world for decades. France has 58 operating nuclear power plants, second only to the 104 operating nuclear power plants in the United States. In contrast to U.S. nuclear power plants, French nuclear power plants have only a relatively few years of on-site storage capacity for SNF. After a cooling period on site, SNF is shipped from a reactor to a centralized storage facility located at the AREVA plant in La Hague. There, the SNF is either stored temporarily or reprocessed.

The French waste-management program includes a complex system of at-reactor and centralized storage; transportation by road, rail, and water; reprocessing; and fuel manufacturing from plutonium recovered by reprocessing. In addition to dealing with all of the spent fuel produced in France, the French waste-management program also receives, stores temporarily, and reprocesses spent fuel from other nations and ships back products from reprocessing to them. The only element of a waste-management system missing at the present from the French system—as it is from the waste-management systems of all countries—is a deep geologic repository for permanent disposal of high-activity nuclear waste.

Like France, Sweden also has a highly integrated, advanced, and complex waste-management system that operates efficiently. The Swedish waste-management system is somewhat less complex than France's, because Sweden has fewer operating reactors (10 versus 58 in France) and because it does not include a reprocessing facility, does not have significant shipments of waste to or from other countries, and can depend primarily on transport by sea. Like France and unlike the United States, Sweden does not have extensive storage capabilities at the reactor sites. Instead, SNF is shipped to a large, centralized interim storage facility at Oskarshamn, where it awaits final disposition.

In contrast to France and Sweden, the United States has relatively little experience with transportation of commercial SNF and does not have either a centralized storage facility or a reprocessing facility for commercial SNF. There have been several shipments of spent fuel from research reactors, but each of these shipments has been treated as a one-of-a-kind event. The U.S. Navy does have a finely tuned, tightly integrated waste-management system for its SNF that includes a centralized storage facility at the Idaho National Laboratory (INL) and a rail-based transportation system for bringing spent naval fuel to INL.

OCRWM recognized the complexities of the integrated waste-management system that it would need to develop and had a program for planning, constructing, and operating an integrated system for managing commercial SNF. The results of that planning are well documented, although the thinking behind the planning is less well documented. Much of the undocumented experience of planning a waste-management system for commercial spent fuel in the United States may be lost permanently without action. (See "The Current Technical Experience Base" section in the next chapter for a recommendation for capturing this experience.) The French experience is likely to be available, as well as the experience of other countries operating complex waste-management systems. Those programs, the U.S. Navy program, and their histories, should serve as valuable resources for informing future U.S. programs.

4.4. CONTRIBUTION OF MULTINATIONAL AGENCIES TO REPOSITORY DEVELOPMENT PROGRAMS

Two multinational organizations, the International Atomic Energy Agency and the Nuclear Energy Agency, have played important roles in the development of radioactive waste-management programs in the United States and abroad. OCRWM and the Nuclear

Regulatory Commission have been active in both organizations, although OCRWM's participation has been limited because the oxidizing tuff of Yucca Mountain differs from the reducing geologic media of repository programs of all other countries with active repository programs. If the United States redirects its efforts away from the Yucca Mountain program, both international organizations are likely to be still more influential on the U.S. waste management and disposal program in the future. In particular, many of their contributions will be viewed through eyes not constrained by the programmatic interests specific to the Yucca Mountain program.

International Atomic Energy Agency (IAEA)

The IAEA was set up in 1957 as an autonomous organization reporting to the General Assembly and Security Council of the United Nations. The agency works with its member states and multiple partners worldwide to promote peaceful nuclear technologies. Guided by the interests and needs of member states, the IAEA's mission is threefold: safety and security, science and technology, and safeguards and verification.

Until relatively recently, most of the effort of the Nuclear Fuel Cycle Division in IAEA's Department of Nuclear Energy was directed toward transferring information and technology for managing low- and intermediate-level nuclear materials, including medical isotopes and decommissioning waste. Greater attention is being paid now to high-level radioactive waste and spent nuclear fuel. The division, for example, sponsors training seminars that are attended by leaders of nuclear waste-management organizations from countries that are only just beginning to consider how to implement geologic disposal.

Most of the division's energy and resources are directed toward the publication of TECDOCs (technical documents). The Division published or will soon publish TECDOCs addressing, among other things, the use of anthropogenic analogs, the technical implications of retrievability for geologic repositories, the applications of numerical modeling, and factors affecting public and political acceptance of disposal facilities. These TECDOCs are an important resource for nations with modest waste-management programs. For nations with larger programs, the TECDOCs can provide a vehicle for demonstrating that approaches taken by a particular national program are consistent with international practice and opinion.

The Division of Radiation, Transport, and Waste Safety within the IAEA's Department of Nuclear Safety and Security publishes three different types of safety standards. *Safety Fundamentals* are policy documents that state the basic objectives, concepts, and principles involved in ensuring radiological protection and safety. *Safety Requirements* are derived from the *Safety Fundamentals* and are written as "shall" statements. They may be used as a basis for national regulations. *Safety Guides* contain recommendations on how to meet the requirements. They use "should" statements and are based on international experience. In 2006, for example, a *Safety Requirements* document for geologic disposal was released (IAEA 2006).

The IAEA's Waste Safety Standards Committee oversees the process for preparing all safety standards. The IAEA staff, exercising considerable discretion, invites experts to work on each standard. A standard may be revised a dozen times before it is sent to member states for review. Comments received must be addressed fully because a standard cannot be issued unless there is full consensus among member states. Consequently, standards typically represent the "lowest common denominator" position, which is open to multiple interpretations. In particular, the standard will never directly contradict a stance taken by a member state, especially those with advanced nuclear power programs. Nonetheless, the document can significantly affect regulatory policies in member states. Increasingly, there seems to be a desire on the part of national authorities to promulgate regulatory standards that appear to be "harmonized" with the standards established by other authorities.

Nuclear Energy Agency (NEA)

The NEA is a specialized agency within the Organization for Economic Cooperation and Development, an intergovernmental body whose membership includes 33 developed countries committed to democracy and the market economy. The mission of the NEA is to assist its member countries in maintaining and further developing, through international cooperation, the scientific, technological, and legal bases required for the safe, environmentally friendly, and economical use of nuclear energy for peaceful purposes. To achieve this, the NEA works as a forum for sharing information and experience and promoting international cooperation, a center of excellence that helps member countries to pool and maintain their technical expertise, and a vehicle for facilitating policy analyses and developing consensus based on its technical work.

The NEA's work in radioactive waste management is overseen by its Radioactive Waste Management Committee and is carried out by several subsidiary bodies, including the Forum on Stakeholder Confidence (FSC), the Integration Group for the Safety Case (IGSC), the Regulators' Forum, and the Advisory Bodies to Government. Over the last decade, in particular, these bodies have been extremely active, not only providing venues for discussions across national programs but also publishing a voluminous record of deliberations, analyses, and peer reviews. Collectively, these works often represent the state-of-the-art thinking about issues that are likely to confront a redirected U.S. program.

For example, for the last 10 years, the FSC has been focusing on efforts in Canada, France, Finland, and Belgium to bring interested and affected parties more meaningfully into the work of national programs. The record it has produced will provide consensus insights for a redirected U.S. program. Further, the IGSC has done very important thinking about what a safety case should look like and how a national program might advance it (NEA 2008). The IGSC has produced noteworthy technical documents as well. (See http://www.oecd-nea.org/rwm/igsc/.) A redirected U.S. program would benefit from NEA's work, which is innovative and, in many respects, path-breaking.

Importance of Cooperation

Nations with waste disposal programs have a high degree of cooperation and many joint research programs. For example, under the auspices of the Nuclear Energy Agency, countries with interest in repositories located in clay formed a working group in 1990 on argillaceous media, informally known as the "Clay Club," to share experiences and ideas. The Clay Club includes Belgium, Canada, France, Germany, Hungary, Japan, Spain, Switzerland, the United Kingdom, and the United States. Members share data on clay properties and behavior, on methods of testing in clay media, and on specific features, events, and processes specific to long-term disposal of high-activity waste in clay media. Argillaceous rocks may be among the media considered a potential host medium for future U.S. repository programs, and the United States will benefit from its association and cooperation with other countries considering clay.

Many nations with repository programs have independent governmental entities having oversight roles similar to those of the Board, including France, Germany, Japan, Sweden, Switzerland, and the United Kingdom. The Board cooperates with those entities through an informal organization, the Advisory Bodies to Government (ABG), which was established in early 2004 under the auspices of the NEA. The ABG's purpose is to provide a forum for organizations similar to the Board to meet and exchange information and to share experiences in their successes and setbacks in accomplishing their assigned missions.

5. MOVING FORWARD

The Board believes that keeping a focus on a permanent solution is critical regardless of what interim measures for managing high-activity waste are charted. Among the reasons are (1) a permanent solution is critical to building public confidence that there is a way of isolating nuclear waste radioactivity from the biosphere to acceptable levels; (2) given the long duration of the hazard of high-activity waste, undue delay in implementing a permanent solution could make tenuous a concept of waste management dependent on institutional stability; (3) experience to date has indicated that deploying a permanent solution to isolating high-activity waste could take decades; and (4) there is an international consensus that a permanent solution to high-activity waste isolation is feasible via geologic disposal. These reasons are believed to be compelling for a focused effort to implement a permanent solution for disposing of high-activity waste. Although the problems of deployment involve many factors, including institutional and political considerations, this report has focused primarily on the technical issues associated with implementing a permanent solution and technical lessons learned from the experiences of the Yucca Mountain program and other programs.

The Yucca Mountain program has contributed significantly to the technical knowledge base for developing a geologic disposal facility for high-activity waste. As discussed in chapter 3 of this report, major advances were made in assessing the performance of engineered barriers and the natural system associated with geologic disposal. Advances were made in modeling water flow in unsaturated fractured rock in semiarid zones, understanding the role of matrix diffusion in transporting radionuclides, and using analog information as evidence for assessing hydrogeologic behavior of geologic units. Chapter 3 also discusses the important use of systems analysis tools, such as the total system simulation model and quantitative probabilistic risk assessment, to ensure that the repository is integrated with the balance of the waste-management system and to portray the risk of the repository over time. The Yucca Mountain program developed considerable data, methodology, and evidence to indicate the technical feasibility of isolating high-activity waste in an unsaturated, oxidizing environment.

Other programs, both in the United States and abroad, also have contributed significantly to the technical knowledge base for geologic disposal, as discussed in chapter 4. Together, the knowledge gained in the Yucca Mountain program on tuff as a repository medium in an oxidizing environment and the knowledge gained in other programs in other geologic media and reducing environments are a very strong technical base for moving forward with geologic disposal in the United States.

The worldwide experience to date strongly suggests that the steps necessary to move forward technically in an efficient and cost-effective manner are the following:

(1) ensuring that the Yucca Mountain and international knowledge and experience base are available and accessible to future U.S. repository developers

(2) developing an experience-based site-selection and site-characterization process that incorporates systems-analysis methodology

(3) characterizing existing and new waste forms in concert with existing inventories of high-activity waste

(4) developing organizational and project plans for site selection and characterization and for design, licensing, construction, and operation of a geologic disposal facility for high-activity waste and integrating the plans with the entire waste-management system.

ENSURING THE AVAILABILITY AND ACCESSIBILITY OF THE CURRENT TECHNICAL EXPERIENCE BASE

There are several decades of experience involving tens of millions of person-hours dedicated to developing geologic disposal as a permanent solution for isolating nuclear waste from the biosphere. This has come about because of the international consensus that geologic disposal is at least a necessary part of the solution for managing high-activity waste. The experience base involves different geologic media, different concepts for engineered barrier systems, different waste forms, and extensive use of performance assessments, including probabilistic risk assessments. The knowledge base for geologic disposal has increased immensely in the last two decades.

Much (but not all; see below) of the experience base of the last several decades is available in the form of technical papers and technical reports. Highly detailed technical information, such as detailed engineering drawings and detailed descriptions of experimental apparatus, tends to be less available. Detailed drawings are on the Licensing Support Network (LSN), but the legibility of the drawings often is poor. Obtaining original (paper) drawings is a laborious process. One would not expect that such detailed information would be sought early in the process of moving forward, however. The action needed to begin moving forward is ensuring that relevant technical information is readily available and accessible. Because many of the programs and models were run on hardware that may not be readily available in a few years, DOE should preserve not only the software (computer codes) but also the hardware, without which the codes cannot be run unless completely rewritten (a huge and unnecessary undertaking).

Much of the Yucca Mountain experience base is currently available and accessible through the LSN. Although the extreme redundancy of data in the LSN limits its value, a key first step would be to ensure that the LSN remains available. There is nothing comparable to the LSN for the international experience base. Accessing the information of other countries would entail international cooperation, such as discussed in chapter 4. The first steps of any new program should be to forge strong bonds with the waste-management and disposal programs of other countries, both directly and through the auspices of the IAEA and the NEA.

Some of the bases for technical decisions can be found in presentations made by DOE managers and M&O and National Laboratory technical personnel to the Nuclear Waste Technical Review Board and to the Nuclear Regulatory Commission's now-defunct Advisory Committee on Nuclear Waste (ACNW). The Board has been holding public meetings since 1989. Overheads and transcriptions of presentations made at the meetings are available at the Board's Web site, www.nwtrb.gov. The ACNW held meetings from June 1988 until May 2008. Many of the overheads and transcripts of presentations at those meetings can be obtained from the Nuclear Regulatory Commission's Web site, www.nrc.gov.

Despite the information in TMRB[34] minutes, the NWTRB and Nuclear Regulatory Commission Web sites, and other available program documents, answers to the questions about the rationale underlying technical decisions still remain unavailable. This is unfortunate from a lessons-learned viewpoint, because understanding the reasoning behind Yucca Mountain decisions would help future repository developers emulate past good decisions and prevent repeating past mistakes and poor decisions. Information about the decisions resides with former senior OCRWM personnel, DOE contractor personnel, and USGS and National Laboratory personnel formerly associated with the program. Very few are working in the field of high-activity waste management today. Locating them soon and obtaining their retrospective views and insights could be very helpful to future developers.

SITE SELECTION AND CHARACTERIZATION

The Board came into existence in 1987 at the same time that Yucca Mountain was designated as the only site to be characterized for hosting a geologic repository. Ten years of characterizing Yucca Mountain for a repository already had taken place by 1987. Thus, the Board was not involved in site selection or in the first decade of site characterization.

[34] The Technical Management Review Board (TMRB) was a panel of senior technical managers of the M&O contractor located in Las Vegas (BSC 2002).

The Board believes, however, that probabilistic risk assessments were not used in the site-selection process, partly because EBS designs for the various sites under consideration had not been developed. The Board believes that using PRAs to compare sites is now feasible because EBS designs appropriate for various geologic media have been developed by many programs. The Board notes, however, that the collective Yucca Mountain, WIPP, and international experience to date strongly suggests that repositories can be developed in many geologic media. Deciding factors for site selection, therefore, may well be nontechnical. Nonetheless, *the Board recommends that PRA be used as part of the site-selection process and during site characterization.* The level of complexity of PRAs developed to assist site selection and characterization should be appropriate for the site-selection and site-characterization questions at hand. That is, they should be considerably less complex than PRAs developed for licensing purposes.

THE WASTE FORM

Some of the DOE-owned SNF degrades more rapidly when contacted by water than commercial SNF. Depending on the medium for geologic disposal, this suggests that tradeoff studies could be performed to assist in determining the relative advantages of treating some of the DOE-owned SNF to improve its performance in a geologic environment. Treatments considered could include (1) chemically treating the DOE-owned SNF to obtain a more resistant waste form; (2) chemically separating the radionuclides and then treating and packaging each separated component in a manner commensurate with its risk; and (3) repackaging or overpackaging the DOE-owned SNF to delay the time when water reaches the waste form.

Vitrification of liquid waste into a highly stable borosilicate waste form was selected three decades ago. There is considerable experience with vitrification at full scale at the Savannah River Site, at West Valley, and at the La Hague plant in France and the Sellafield plant in the United Kingdom. Research continues on vitrification to improve the percentage of waste that can be incorporated into the waste form while maintaining its long-term durability. Research also continues on ways to improve processing equipment, increase throughput, and reduce overall processing costs. Some U.S. high-activity waste, e.g., vitrified HLW at Savannah River, is significantly less hazardous than commercial SNF on a volumetric basis or on a per-waste- package basis (see SNL 2008a: Table 6.3.7-3). Treating such wastes more aggressively or packaging them more robustly than commercial SNF is treated or packaged makes no sense because commercial SNF is the dominant contributor to repository risk.

Depending on the geologic medium, the waste form can be a critical factor when it comes to a permanent solution, such as geologic disposal. The waste form is part of the strategy of engineering into the repository an EBS that substantially delays arrival of radionuclides at the natural system, thereby gaining a major benefit from radioactive decay. Planning a geologic disposal facility requires extensive total system analysis and trade-off studies to determine acceptable and appropriate waste forms and EBS designs for a specific site. That is, the waste form can be optimized only on a site-specific basis. As discussed in chapter 2, the wide variety of U.S. waste forms compels the United States to choose among several alternatives: seek a single disposal system that can accommodate them all; process or package the wastes into more-or-less standard forms for disposal; or develop separate geologic disposal facilities for different classes of wastes. Current waste-form characteristics and inventories should be reexamined, and the issue of the appropriate disposal method for each waste form should be addressed. Many previous decisions about multiple repositories, waste processing and packaging, and repositories dedicated to classes of wastes were made in a Yucca Mountain context. These decisions will have to be made again. Trade-off studies may inspire new ideas on waste management, such as one type of geologic disposal for most of the waste, e.g., waste that is retrievable, and another type of disposal for waste that may involve vitrified waste, less stable spent-fuel assemblies, or even damaged fuel. Such wastes may be better suited for other measures, such as deep boreholes, where retrieval may be difficult or impossible. Such separation of wastes may allow greater flexibility in siting facilities and improved confidence in the performance assessments.

DEVELOPING INTEGRATED ORGANIZATIONAL AND PROJECT PLANS

Lack of integration among various aspects of the Yucca Mountain program is discussed in sections 1, 5, and 6 of chapter 3. The relative success of other programs, notably the WIPP program and the Swedish program, provides strong evidence that several Yucca Mountain program deficiencies could have been prevented if a total integrated systems approach had been adopted.

Perhaps the biggest challenge to moving forward with a permanent solution to managing high-activity radioactive waste is developing the right kind of project plan and an implementing organization that is capable of adapting as technical needs change from primarily scientific to primarily engineering. From the beginning, the organizational culture has to be one of actually building something on time and within budget that meets all technical specifications and relevant local and federal regulations. At the same time, until a site is chosen, characterized, and found suitable, there is no project to plan. Site characterization itself is fundamentally a science program, but one that must take engineering considerations into account. Scientific activities can be scheduled but not scientific results. On the other hand, with the rich worldwide experience base in characterizing different geologic media for repositories, the time needed to characterize a specific site might be bracketed. In any case, the transition from engineering serving science to science serving engineering is not a sharp one.

Because site selection, site characterization, and repository engineering are such different projects, consideration should be given at the outset to the appropriate skills, organizational form, and even institutional form for each project. The Yucca Mountain program was a mix of science and engineering, with the resulting conflicts of authority and management of the two disciplines. The transition between science and engineering in a first-of-a-kind program that involves new knowledge and technologies is sometimes difficult to resolve. *Nevertheless, the lesson learned is that it is important to establish the point at which the science part of the program assumes a supporting role to the engineering. In particular, once the project becomes an engineering project, the technical and scientific needs of the project should be driven by what it takes to engineer the project to its performance goals.*

The Yucca Mountain program management began to change from a science project to an engineering project a few years before the formal recommendation of the site by the Secretary of Energy in early 2002. However, the science, although sufficient for the formal recommendation, was not sufficient for the documentation and performance assessment required for the license. In addition, developing the TSPA-LA itself was treated much more as a science project than an engineering one. Whether envisioning and managing the project as an engineering one from the very beginning would have resulted in a better outcome is a question that deserves to be addressed. *The end product is clearly an engineering one, and engineering could guide the science even from the beginning of site selection.*

CONCLUDING REMARKS

As a result of the activities of the Yucca Mountain program and other repository programs for high-activity waste over the last several decades, the knowledge base for disposing of high-activity waste has grown significantly. Key accomplishments of value to future repository development programs include the following:

- submittal of a license application that the Nuclear Regulatory Commission found acceptable for review
- development of an engineered barrier system design that, according to the license application, will perform as a significant barrier for 1,000,000 years
- development and application of methods for evaluating the performance of geologic units involving unsaturated zones in an oxidizing environment
- development of additional evidence that many different geologic media, including unsaturated tuff in an oxidizing environment, have the potential to host geologic repositories
- substantial evidence that engineering may be used to turn less-than-technically-optimal repository sites into better ones

- establishment of probabilistic risk assessment as the principal method for measuring the risk of a repository
- trade-off studies on the appropriate waste form, packaging, and geologic media for various high-activity wastes
- insights on the best institutional form(s) for the various phases of a repository project, how to transition from one phase to another, and whether a single institutional form can be appropriate for all phases.

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APPENDICES

APPENDIX A-1

EVOLUTION OF THE CONCEPTUAL DESCRIPTION OF ATMOSPHERIC DUST AND THE WASTE-PACKAGE CORROSION ENVIRONMENT

The conceptual description of the waste-package corrosion environment that is due to the deposition of atmospheric dust on the metal during preclosure ventilation evolved considerably over the life of the Yucca Mountain program. What has changed is the description of the composition of the dust, what happens to the dust in a chemical reaction sense, and the effect of radiolysis. That the dust layer on waste package surfaces is a dynamic reacting chemical system with a continual supply of reactants has been known for about 10 years. Yet today, there is no complete conceptual description of the corrosion environment on a waste package's metal surface.

The major topics that bear on the evolution of the conceptualization of the corrosion environment on a waste package as affected by atmospheric dust are the existence of calcium chloride in and on atmospheric dust (Prather 2010); the existence of organic matter in and on atmospheric dust (Gelencsér 2004); the reaction of organic matter and nitrate in dust that depletes the nitrate content (Peterman 2008); radiolysis effects, including gamma radiation of chloride salts producing halogen bubbles within the salt (Dubinko et al. 2000); and the radiolysis of moist air producing oxides of nitrogen and specifically nitric acid (Tang and Raduescu 2002). Examination of the details of these five major topics leads to the conclusion that the corrosion environment as described at the time of the *License Application Design Selection Report* (CRWMS M&O 1999) is incomplete. A brief discussion of the five topics follows.

Calcium chloride in and on atmospheric dust is considered rare from a geologic perspective because its natural existence on the surface of the earth occurs at only two places: in Antarctica and California (Dunning and Cooper 1969). Dust and its components lofted into the atmosphere from the earth's surface are called *primary* components. Dust components generated by chemical reaction in the atmosphere are called *secondary* components, and, except for the rare situation of Bristol Dry Lake in California (which is actively mined for calcium chloride), calcium chloride is the product of the reaction of calcium carbonate (calcite) and hydrogen chloride in the atmosphere, as noted by Prather (2010) and Sullivan et al. (2007). Calcite is ubiquitous in atmospheric dust as a primary component.

Therefore, it also is possible to conclude that dolomite and hydrogen chloride will react and result in the production of magnesium chloride as a secondary component, along with calcium chloride. The observation that atmospheric dust contains organic matter is beyond question. Books have been published on this topic, and the publications are too numerous to cite here. The book by Gelencsér (2004) is an excellent starting point for becoming familiar with this topic.

The hypothesis that organic matter and nitrates can react was put forth in early 2007 because of the recognition that organic matter is a reducing agent and nitrate is an oxidizing agent, and thus these two components can react, resulting in the loss of nitrate and organic matter (Garrick 2007). Although the progress of reaction cannot be readily predicted at ambient or near-ambient temperatures, the thought at the time was that the local corrosion-environment temperature of a waste package in Yucca Mountain could be high enough for this reaction to proceed at an observable rate. This turned out to be the case, as demonstrated by experiment by Peterman, previously cited, where nitrate loss from heated atmospheric dust was reported to occur over a time span of days; minimal loss of chloride was observed. This particular experiment was not conducted in exactly the same environment expected in a repository: Ambient air prevailed, so the sample was considered dry. In a repository, the dust would be subject to a higher-humidity environment after closure, and with more water present, the phenomenon of acid-gas devolatilization could occur. Acid-gas devolatilization is a process in which hydrogen-chloride gas is lost from an aqueous phase. If this phenomenon were to occur, the corrosion environment eventually would experience a low chloride concentration. However, no experiments have been reported that directly demonstrate this phenomenon, and conclusions have been reached through indirect observations.

Radiolysis effects on the dust-humid air environment on waste package surfaces have not been considered, but well known is that gamma radiation can break chemical bonds, producing myriad chemical species, including free radicals. The effect of radiolysis on uranium oxide dissolution has been noted, where water radiolysis produces oxidizing and reducing species, including radicals (e.g., OH^-, O_2^-, HO_2^-, e^-_{aq}, H^+) and molecular species at concentrations that depend on the type of radiation (α or β-γ) and the dose deposited in the water interface (redox imbalance with the environment), and thus enhances the dissolution of the oxide layer protecting the waste package (Frizon et al. 2009). Similar effects may occur for any oxide. In the case of the exposure of alkali halide salts to gamma radiation, halogen bubbles have been observed, as reported by Dubinko (2000). The effect of radiolysis was noted in the Climax Spent Fuel Test where it was observed that all 11 carbon steel liners that had contained spent fuel showed much more evidence of external corrosion near the top of the fueled section than those containing electrical simulators (Weiss et al. 1985). The effect of gamma radiolysis on stress corrosion cracking has been described by Andresen

(1992), who writes, "While IASCC (irradiation-assisted stress-corrosion cracking) is of primary interest in light water reactor core materials, it is also of concern in applications such as fusion reactors and high-level radioactive waste containers." At this time, there is no discussion of the effect of chloride on IASCC in Yucca Mountain program documents.

The fact that organic matter and nitrate can and do react, resulting in the loss of nitrate, may not be the end of nitrate (Peterman 2008). Oxides of nitrogen and nitric acid (secondary components) are produced by gamma radiolysis in moist air in the immediate vicinity of a waste package, as described by Tang and Raduescu. So, the situation exists now where nitrate may be produced and sorbed onto a waste package surface in a postclosure environment after the organic matter has been consumed by this continuous nitrate source. A material balance taking into account the kinetics of organic loss and nitrate production has not been completed. If this situation is subsequently shown to be the result, the corrosion environment will be nitrate-rich. It is clear at this time, though, that all the effects described here evolve with respect to time, and there is no material-balance description available that takes all these effects into account.

The conceptual description of the corrosion environment of a waste package determined in part by atmospheric dust clearly has evolved in comparison to the description of 10 years ago. The experience gained in this evolution applies to a description of any corrosion environment that results from exposure to the atmosphere and especially that expected for the long-term dry storage of spent nuclear fuel on the Earth's surface, where natural-convection cooling using the atmosphere will be implemented. We believe that most, if not all, future repositories will have extended preclosure periods. That is, the duration of the time between emplacement of a waste package and closure of the repository may be measured in decades. Dust will be deposited on waste packages surfaces during that period, and the composition of the dust will be affected by the five major factors discussed in this appendix. The composition of the dust determines the corrosion environment during the preclosure period and influences the corrosion environment during the period that begins immediately after closure. Thus, studying the evolution of the surface environment of the waste packages is important for any future repository.

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APPENDIX A-2

ITERATIVE NATURE OF GEOLOGIC SITE INVESTIGATION AND CHARACTERIZATION

In 1994, the Board held a meeting to review the successes and failures of various attempts to site and license large engineering projects, such as nuclear waste repositories, power plants, and dams (NWTRB 1994). On the basis of the meeting and subsequent analysis, the Board offered several insights and lessons learned that it believed would apply to the Yucca Mountain site characterization. Two related directly to geology: (1) Site assessment requires a strategy that is an iterative process that continually looks at the relationships among data gathering, modeling, and performance assessment; and (2) Expect surprises in any underground site investigation. Geologic surprises certainly appeared over the years of investigation at Yucca Mountain and affected the evolving conceptual model of site geology and repository design. DOE and the Yucca Mountain program remained sufficiently flexible to incorporate the surprises into project knowledge and modeling, but surprises sometimes led to project delays.

Formal site-characterization work began at Yucca Mountain in 1977. Using surface geological mapping supplemented by preliminary borehole data, DOE constructed a preliminary subsurface conceptual model of site geology, which looked like **Figure 1** (next page) in 1988. Figure 1 was based on data from more than 180 boreholes and 20 excavated trenches. The repository was expected to be located in the lower nonlithophysal zone, toward the bottom of the Topopah Spring rock unit (DOE 1988b: 1-326). Considerable additional site investigation was planned. Knowledge of all important geological rock units and features (for example, earthquake faults and rock fractures) was needed not only to design and construct the underground tunnels and rooms but also to predict the mechanical, thermal, hydrological, and geochemical behavior of the natural system far into the future.

Since its first meetings in 1989, the Board emphasized the importance of gaining direct access to the underground at Yucca Mountain by excavating tunnels or drifts across all major geologic features at the site. As of 1993, DOE had prepared detailed site-investigation plans for tunneling through the mountain at various levels and across all geologic units to allow visual examination of the complex geology and to characterize the major geologic

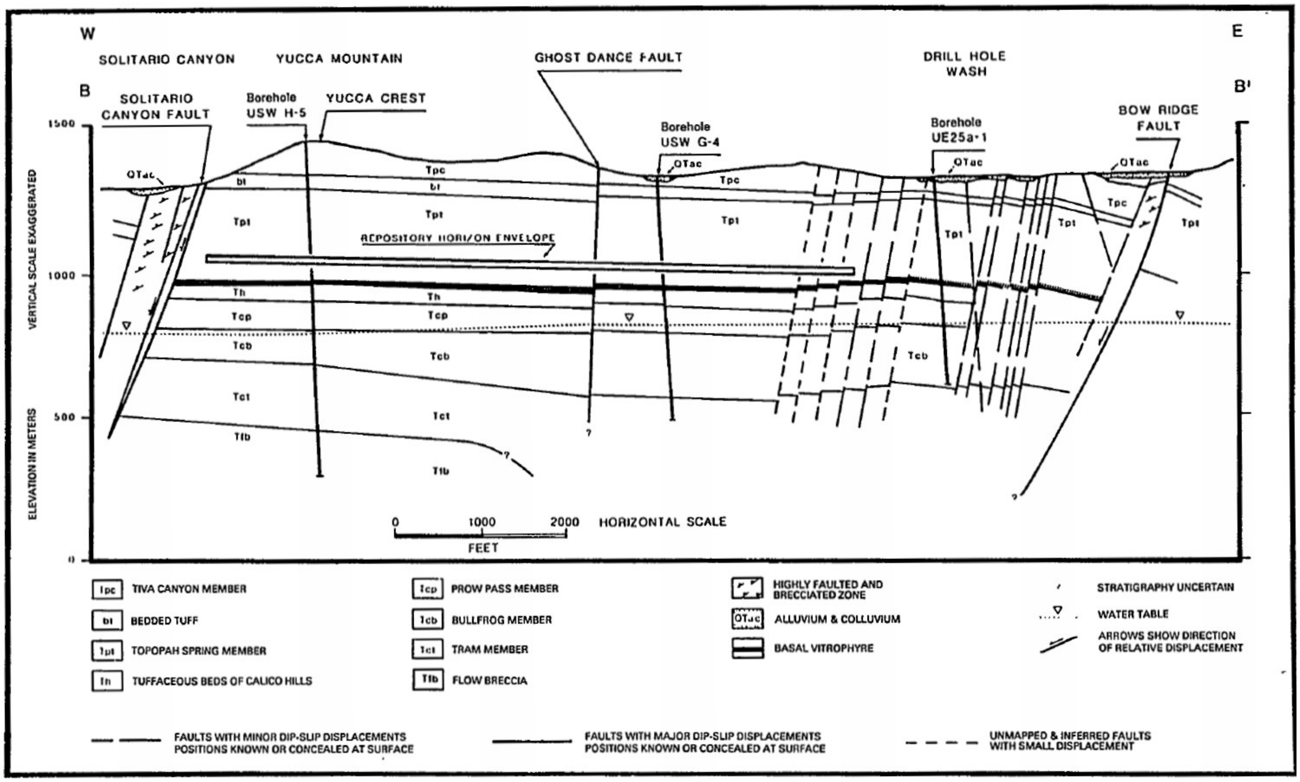

Figure 1. East-west geologic model of Yucca Mountain in 1988 (DOE 1988a: 19)

features in the planned repository block. The plans included extensive tunneling into Yucca Mountain: 8 tunnels and 88 rooms or "alcoves" for conducting in situ scientific tests. An unexpected 40 percent budget cut for the program in 1994-95 led to a significant reduction of tunneling plans. The first exploratory tunnel, the ESF, was started in September 1994 by a tunnel-boring machine and completed in April 1997 for a total distance of almost 5 miles.

The ESF confirmed the basic model of rock strata, but the rock mass's structural quality and expected number and nature of structural features (faults, major fractures, joint planes, and lithophysae) proved quite different from what was expected. Testing in the ESF also revealed the possibility of fast flow paths from the surface and long-term average flows that were 10 times faster than previously thought. The new information resulted in many changes to the project assumptions.

The ESF tunnel did not extend down deep enough to expose the rock where most of the repository was planned to be built. When DOE became reluctant to carry out additional tunneling because of budget cuts and schedule pressure, the Board stated, "It is the Board's position that a technically defensible evaluation of the site cannot be made without exploration that would eliminate or greatly decrease the potential for a major geologic surprise subsequent to the decision. The Board continues to believe that an east-west crossing of the geologic block west of the Ghost Dance Fault (i.e., the upper waste emplacement block) is necessary prior to any technically defensible decision on site suitability." (NWTRB 1996: 23)

In early 1997, the Board repeated its position and added, "The Board believes that determining the existence and abundance of fast flow paths can best be accomplished by excavating an east-west tunnel through the potential repository block west of the existing ESF (NWTRB 1997: 8)." DOE accepted the Board's recommendation for building the ECRB, a small-diameter east-west exploratory tunnel to be driven across the proposed repository block, and began excavating the ECRB by tunnel-boring machine in December 1997. The work was completed in October 1998, extending 1.6 miles from the ESF start point (the right side of **Figure 2**). The ECRB permitted observation of rock conditions at a different orientation than in the ESF, involved tunneling through the full range of repository rock units, and provided access to mine test rooms for scientific testing in new areas.

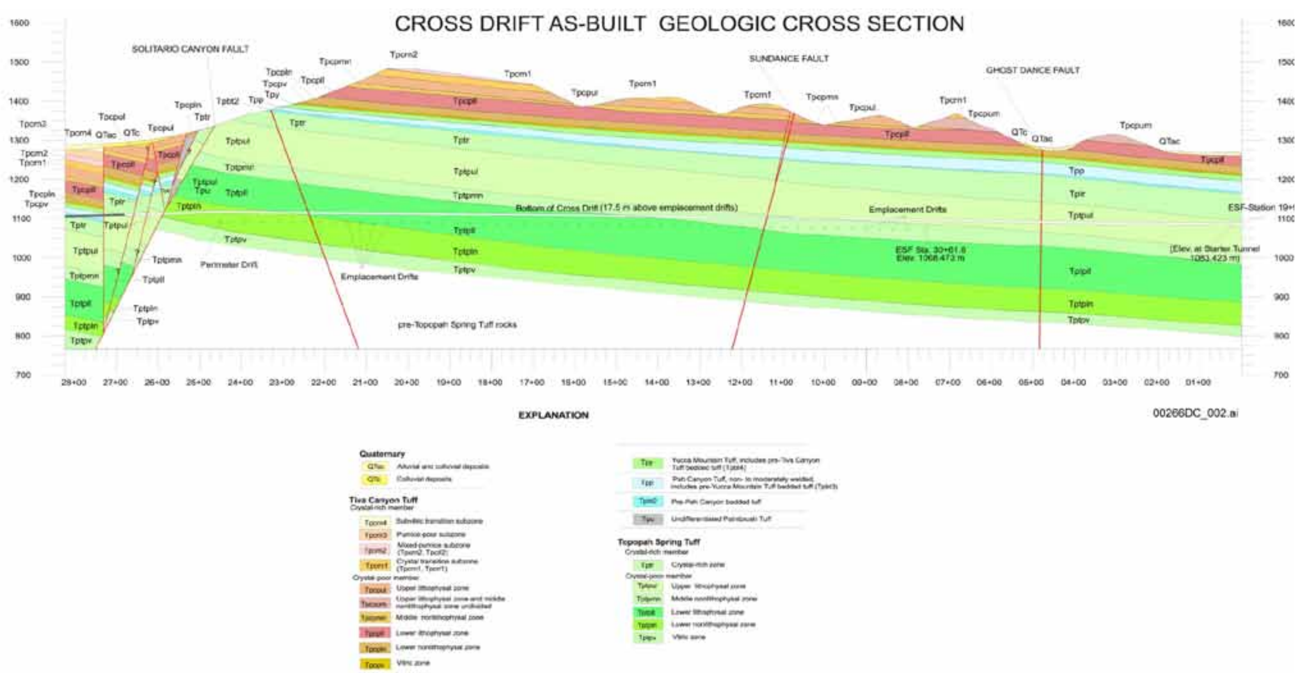

Figure 2. Enhanced Characterization of the Repository Block (Cross Drift)

New scientific insights were gained with information from the ECRB that affected the Yucca Mountain program. Fast-flow pathways of water were confirmed. Geologists formally identified the four key lithostratigraphic rock units (Tptpul, Tptpmn, Tptpll, Tptpln) in the proposed repository horizon on the basis of rock features (primarily lithophysae and fractures). Visual inspection of these units led to adoption of a more detailed geologic model in comparison to the model consisting of two thermo-mechanical geologic rock units (TSw1 and TSw2) previously used. By 2002, DOE had relocated the repository from the Tptpln rock unit (planned location in 1988) to mostly (~80 percent) within the Tptpll rock unit. The

Tptpul upper lithophysal and Tptpll lower lithophysal units were significantly different from the Tptpmn and Tptpln nonlithophysal units, having different mechanical, thermal, and hydrological properties. Most of the hundreds of borehole specimens that were tested turned out to be biased because lithophysae were not well represented in the 1- and 2-in.-diameter borehole core specimens. The ECRB and its test alcoves also revealed important information about in situ rock moisture, major fault features, failed lithophysae or "spot" features, data needed to improve the three-dimensional geologic rock model, and various rock properties.

Yucca Mountain geology has not changed over the years of investigation; only human knowledge about the geology has changed. Inevitably, any investigation of future repositories will encounter its share of surprises, and the understanding of the geology will evolve, particularly after underground access is provided.

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APPENDIX A-3

THERMAL MANAGEMENT

The Board expressed interest in DOE's Yucca Mountain repository thermal management strategy that resulted in the repository design layout, designation of a single thermal loading, and preclosure operations based on this single thermal loading that appear in DOE's license application. The repository design characteristics, which are a direct result of DOE's thermal strategy, are a drift spacing of 81 meters, an axial waste package spacing of 0.1 meter, designation of a single thermal line load at emplacement of 1.45 kilowatts/meter with a specific rate of decay, and preclosure forced-air ventilation (CRWMS M&O 1999).

Over many years, the Board questioned the thermal management strategy. DOE's thermal management strategy did evolve because of, in part, more time-efficient thermal analysis techniques, but the evolution did not include varying thermal loads for use in the Total System Performance Assessment (SNL 2008). The more time-efficient thermal analysis techniques that came into existence include the ventilation calculation, where decay heat from emplaced waste packages is removed by forced ventilation of ambient air through the repository to remove a significant fraction of the heat. This ventilation analysis initially required so much time that various thermal strategies simply could not be analyzed thoroughly. However, as time passed, thermal analysis techniques were improved to the point where many thermal analyses could be completed in much less time.

The improved ventilation analysis resulted in computational times of seconds compared with many hours previously (Walsh 2004). The purpose of the ventilation analysis was to calculate how much heat from waste packages would be transferred to the host rock and how much would leave the repository in the ventilation air flow. The result of the ventilation analysis was a fraction, called the "ventilation efficiency," that denotes how much heat leaves in the flowing air relative to that produced in the waste packages.

DOE's approach originally was based on numerically integrating the classical transient heat-transfer equation for a solid for the entire mountain at every time step—a conceptually correct approach but one that required computational times on the order of many hours. The improved ventilation analysis is based on the fact that the classical heat-transfer equation for a solid is linear and that a description of rock temperature can be derived from the temperature response of the rock that is due to a single short pulse input of energy. The temperature of the rock can be computed for any transient heat source from the single-pulse response, and the single-pulse response is calculated only once analytically and used over and over to move the analysis forward in time. This technique, known as "superposition," eliminated the numerical integration step. The same mathematical approach applies to the postclosure situation, where there is very little air flow. The improved computational approach enabled analyses of a loss-of-forced-ventilation condition, where the flow occurred only because of buoyancy, also called "natural convection," of heated air in the vertical ventilation shafts. The ability to perform thermal analyses on the order of seconds allowed the investigation of many thermal strategies; this could not be done previously.

The Board undertook thermal analysis efforts so that it would be in a position to understand better the various thermal issues and to direct questions to DOE from a position of informed inquiry. As in DOE's thermal analysis, the Board based its thermal analysis efforts on classical heat-transfer theory and models. However, the Board used different mathematical-solution techniques from the literature. To ensure that the Board's calculations were correct, the Board compared its results with those of DOE and found close agreement. The Board's efforts showed that any waste package that could be shipped from a power plant to the repository could be emplaced in the repository immediately on receipt without exceeding any repository thermal criterion (Rowe and Kirstein 2008). This result essentially eliminated the need for temporary storage at the repository. In contrast, the emplacement pattern called for in the license application required either that the thermal power of shipped waste packages be closely controlled or that waste packages be accumulated in storage at the repository until they decayed to an appropriate thermal power level for emplacement.

DOE also completed thermal analyses for a range of anticipated repository thermal loadings and concluded that through additional thermal management strategies, such as increased spacing between hotter packages and longer preclosure ventilation periods, the anticipated thermal-power range of packages that could be shipped could be accommodated satisfactorily (i.e., immediately emplaced) in the repository (Hardin 2008).

The effective thermal conductivity of crushed rock (e.g., backfill and rockfall granular material) is needed for thermal analyses. DOE's M&O contractor estimated that the nominal diameter of backfill and rockfall granular material in a Yucca Mountain repository would be 10 centimeters (BSC 2004). Classical methods for estimating the effective thermal conductivity of crushed rock from intact rock properties do not apply, because they assume that the nominal diameter of the granular material is on the order of that of sand. In contrast to the effective thermal conductivity of fine-grain material such as sand, the effective thermal conductivity of coarse-grain material is strongly influenced by radiant-heat transfer through the voids between the particles (Buscheck 2005). In fact, the effective thermal conductivity of coarse crushed tuff is two to three times greater than the thermal conductivity of fine crushed tuff. This has been experimentally verified (Osnes et al. 2008). Thus, the thermal effects of backfill and rockfall granular material around a heat-producing waste package now can be analyzed for any repository with greater accuracy and confidence.

The improved method for estimating thermal conductivity of granular material and more-efficient computational techniques are applicable to future repository analyses and will yield improved prediction of the thermal environment.

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APPENDIX A-4

SUMMARY OF THE OCTOBER 2010 U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD MEETING ON LESSONS LEARNED FROM HIGH-ACTIVITY WASTE MANAGEMENT AND DISPOSAL EFFORTS IN THE UNITED STATES AND OTHER COUNTRIES

On October 26, 2010, the U.S. Nuclear Waste Technical Review Board held a public meeting in Dulles, Virginia. The theme of the meeting was "Technical Experience Gained During Development of the Yucca Mountain Repository Program." The purpose of the meeting was to elicit technical lessons that would be of value to future U.S. efforts in waste management and disposal. The Board invited interested parties having involvement in or knowledge of the Yucca Mountain repository program to provide their views of lessons that could be learned from the U.S. program from their individual perspectives.

The meeting was organized into three panels: Panel I, which was composed of former Yucca Mountain managers, scientists and engineers, and contractors; Panel II, which was composed of representatives of affected state and local governments; and Panel III, which was composed of representatives of key programs in other countries.

Some selected highlights from the discussions are presented below. Transcripts from the meeting and the full presentations of meeting participants can be viewed on the Board's Web site at www.nwtrb.gov.

PANEL I: VIEW FROM WITHIN THE YUCCA MOUNTAIN PROJECT

Yucca Mountain in Nevada was designated in the 1987 amendments to the Nuclear Waste Policy Act as the sole site to be characterized for its suitability as the location of permanent geologic repository for the disposal of high-activity nuclear waste. Following the designation, an extensive program was initiated to continue investigating the site, which had been under investigation as a potential repository site for 10 years, and to design a repository that would combine engineered and natural barriers for isolating radionuclides from the accessible environment for millennia.

This first-of-its-kind effort involved many activities in addition to characterizing the site and designing the repository, including developing an estimate of the system performance of the repository that would become part of a repository license application; designing a waste-management system, including packaging and transporting the waste; and anticipating and planning the design and operation of the repository surface facilities. Many talented scientists and engineers were involved in this technical and scientific effort, and the Board invited some of them to present and discuss their thoughts at the October 26, 2010, meeting.

The panel members were Dr. Russell Dyer, former Yucca Mountain Project Manager and Chief Scientist; Mr. Tom Coleman, former Subsurface Engineering Manager for USA RS; Mr. Ted Feigenbaum, former General Manager, Bechtel-SAIC Company, LLC; and Dr. Jean Younker, former Deputy Assistant General Manager, Bechtel-SAIC Company, LLC.

The panel was asked to address the following questions:

1. What technical advances were made during development of the program that would be applicable in developing future programs for management of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) in the United States?

2. What scientific research or technical development work would be undertaken now or in the near term to support future development of a repository for disposal of SNF and HLW?

3. How did different managerial approaches and changes in management approach during the development of the program influence the design, planned operations, and logistics of the Yucca Mountain program?

Selected highlights from the panel presentations and discussion among the panelists and Board members are paraphrased below.

- Integration of science and engineering is very important.
- Flexibility is a key asset in designing a high-activity-waste program and repository; Total System Performance Assessment should be more user-friendly and flexible.
- Focus on validation of models of an ambient, undisturbed site, and then use expert judgment to deal with disruptive events; begin long-term testing on key processes early.
- Frequent changes in budgets and program managers make managing the program challenging; establish long-term capital budgets.
- Use prime contractors who have experience with nuclear projects, and bring them in early.

- Designating a "lead-lab" increases efficiency and effectiveness.
- Prototyping of key engineered components can prevent their becoming critical-path issues and can increase public confidence.
- Design of transportation and storage canisters should be standardized; designs should reflect different requirements and changing needs.
- Direct disposal of dual-purpose canisters should be considered.
- Predicting the performance of materials used for engineered barriers is not difficult if the repository environment is known, but knowing the repository environment is challenging; model results can be very assumption-dependent.
- Decisions should be made on the bases of science, economics, and public safety, not on politics.
- The Yucca Mountain experience would facilitate the characterization of another site in this country because the implementers now know better what kind of questions to ask.
- In terms of site criteria, disruptive events for any site chosen will be key, and climate change will have to be bounded.
- Uncertainty is introduced by changing the standard late in the license preparation process.
- The project took a conservative approach in terms of the overall objective, which was to get Yucca Mountain licensed. Some believe that the conservatisms were excessive or unnecessary.
- Future repository programs should be able to use the existing system model and fine-tune it for the specific site.
- Lack of state and community support helped determine the fate of the Yucca Mountain repository program.

PANEL II: VIEWS OF AFFECTED STATE AND LOCAL GOVERNMENTS

The Nuclear Waste Policy Act directs the Secretary of Energy to make grants to the State of Nevada and units of local governments in the geographical area that would be affected by the Yucca Mountain repository. The purpose of the funding is to enable the state or affected units to develop a request for impact assistance; engage in monitoring, testing, or evaluating activities related to site characterization; and provide and request information. The affected governments included the State of Nevada; Nye County (in which Yucca Mountain is located); Clark County (which adjoins Nye County and in which Las Vegas is located); and other counties abutting Nye County, including Inyo County, California, and the Nevada counties of Lincoln, White Pine, Eureka, Lander, Churchill, Mineral, and Esmeralda.

Some of the affected governments have used a portion of the funding for technical studies that were performed independent of the Department of Energy (DOE). Examples of the subjects of such studies include the following:

- Evolution of environments on waste-package surfaces (Nye County)
- Hydrology of the saturated zone in a southwest direction from Yucca Mountain (Nye County and Inyo County)
- Ventilation methods for heat removal from a repository in Yucca Mountain (Nye County)
- Socioeconomic studies and social perceptions of impacts of Yucca Mountain (Clark County)
- Impacts of Yucca Mountain on national and in-Nevada transportation of SNF and HLW (State of Nevada)

Since its inception, the Board has interacted with representatives of the affected governments and has heard presentations on these studies. The Board invited a panel of representatives of affected governments to present their views on their experiences.

Panel members were Mr. Steve Frishman, Technical Consultant to the State of Nevada; Ms. Abigail Johnson, Nuclear Waste Advisor, Eureka County, Nevada; Ms. Irene Navis, Director of Emergency Management and Homeland Security, Clark County, Nevada; Ms. Connie Simkins, Coordinator of Nuclear Oversight Program, Lincoln County, Nevada; and Mr. Joe Ziegler, Consultant on Nuclear Safety and Licensing, Nye County, Nevada.

The Panel was asked to address the following questions:

1. How has oversight performed by affected units of governments influenced technical decisions related to nuclear waste management and disposal?

2. What factors increased the effectiveness of the technical oversight? What factors might have reduced the effectiveness of such oversight?

3. How does the performance of technical oversight affect the confidence of units of local government and the public in the validity of the technical process?

Selected highlights from the panel presentations and discussion are paraphrased below.

- The perception is that local and state oversight or participation was resisted by the implementer (U.S. Department of Energy) and that comments by affected governments were ignored.
- Oversight should not be categorized as "technical" or "nontechnical" because many of the greatest challenges are institutional; e.g., economic, management, policy, and systems.
- The concept of oversight needs an overhaul, both from the standpoint of the mindset of the implementers and the mechanics of the process.
- State and local governments were not invited to be part of the NEPA process, which reduced confidence in the process.
- The technical process must be valid for affected parties to have confidence in it.
- Communicating technical information so that it is understandable to the lay public is key to increasing confidence.
- Funding of local and state government oversight needs to be adequate and consistent so that affected governments can conduct independent research, monitoring, and reporting.
- In the opinion of some affected governments, the benefits of the repository project were not adequately presented to the public.
- Board meetings provided opportunities for affected governments and the public to interact with the implementers; the charter of the Board should be broadened.
- There should be a federal commitment to local and state oversight, established by law.
- Early access to and transparency of program data are crucial for public confidence
- The U.S. Nuclear Regulatory Commission's relationship with the applicant should be transparent and at arm's length.
- Sufficient time needs to be provided for the public to respond to proposed rule changes and federal decisions.
- If the host state opposes the proposed repository site, nothing will satisfy objections until the project is terminated.
- If affected governments see their comments reflected in decision-making, confidence increases. If they do not see any result from their oversight, confidence is decreased.

PANEL III: VIEW FROM OTHER COUNTRIES

The very-long-term management and ultimate disposition of high-activity waste from commercial nuclear power generation and from defense activities is an increasingly high priority for many countries. Over time, a strong international consensus has emerged that deep geologic disposal is feasible and that it is the preferred mode of disposing of such waste. A broad range of approaches toward developing and siting deep geologic repositories is being pursued by national programs. Each approach takes into consideration the operational needs, geology, and socioeconomic circumstances that are specific to the country in which the repository would be located. The approaches taken by the counties have similarities and differences, and the pace of the programs differ.

Over the years, the Board has interacted with its counterparts in other countries as well as with the implementers of numerous waste-management programs. These international exchanges have been extremely valuable in the Board's ongoing review of DOE repository development efforts in the United States. As part of the Board's discussion of lessons that can be learned from repository development efforts to date, the Board invited representatives of waste-management programs of four countries to provide information on the status of their programs and their views of the Yucca Mountain program.

The panel members were Dr. Enrique Biurrun, Head of the International Cooperation Department, DBE TECHNOLOGY GmbH, Germany; Mr. John Mathieson, Head of International Relations, Nuclear Decommissioning Authority, United Kingdom; Dr. Gérald Ouzounian, Director at the Head of the International Division, Andra (National Agency for Radioactive Waste Management, France; and Dr. Olof Söderberg, Consultant to SKB (Swedish Nuclear Fuel and Waste Management Company), Sweden.

The panelists were asked to respond to the following questions:

1. As you were observing the Yucca Mountain program, what technical approaches seemed to be the most persuasive in terms of making a safety case? Which were the least persuasive? Which seemed to be at odds with the prevailing international consensus?

2. If a new effort for waste management and disposal were to be launched in the United States, what would be the three most important lessons your country has learned that should be taken into account?

3. Which aspects of the Yucca Mountain program and the repository program in your country indicated technical features or developments that should be avoided in developing a repository program in the United States?

Selected highlights from the panel presentations and discussion are paraphrased below.

- When a project (repository) is stopped, it is difficult to move ahead in the future.
- Developing and demonstrating waste isolation in the repository host rock before the repository is licensed is a real advantage.
- A simple component of the waste-management system can be the one that causes the most problems.
- It is helpful to have responsibilities and the steps of repository development established by law (as in the Nuclear Waste Policy Act).
- Financing of repository efforts by waste producers who reimburse expenditures on the basis of multiyear plans has many advantages over the U.S. system of funding disposal activities from the dedicated Nuclear Waste Fund.
- Changes in the U.S. waste isolation concepts (e.g., cool to hot, wet to dry, geologic to engineered) are hard for programs outside the United States to understand.
- Some programs' safety concepts rely on maintaining the integrity of the geologic barrier rather than on meeting a health safety standard for a specified period (as in the United States).
- Countries that recycle have many different kinds of nuclear waste.
- Adopting an approach of "decide, announce, defend" can foment strong local opposition.
- Extensive consultation with the public is important.
- The "government," not the implementer, should lead the effort to find a repository site.
- When efforts to site a repository fail, maintaining a core of competent scientists and engineers with experience in the program and retaining data and information produced by the program are important.
- Involvement and advice by social scientists is important in effective engagement with the public.
- When offering benefits for hosting a site, it is very important that the process be transparent and aboveboard to prevent any appearance of trying to "bribe" the community.
- Until the point that the repository is in the construction phase, it is important that the host community have a veto over the development of a repository.
- Work at the stakeholders' speed.

- Reversability (retrievability) is necessary for public confidence.
- The public may be willing to take the recommendations of scientists related to the underground facilities, but they want a say in the location of the surface facilities.
- The following set Sweden's program apart from the U.S. program: physical magnitude of the waste problem; Sweden's absence of military waste; the differences in governmental systems; program implementer is a governmental entity in the United States, but in Sweden it is a private corporation owned by nuclear power plants.
- In Sweden and other countries, oversight boards have a purview that includes ethical, legal, social, and policy dimensions of waste management. This is a broader purview than that of the NWTRB.
- Decision on going forward should not be postponed into an uncertain future.
- Openness and willingness to discuss difficult issues have been key to the success of the repository program in Sweden. Providing local governments their own money for participating in the process also was key.
- Britain does not have laws governing their repository siting process, so it is done through consultation.
- After failure of a program, several countries have found that it takes approximately 10 years to restart the effort.
- In some countries, opposition to a repository is a way to oppose nuclear activities in general.
- The safety case in some countries is based on a zero release; safety criteria are expressed in dose because the dose is understood better by the public.
- In the UK, safety criteria become more qualitative as the regulatory period gets longer.

PUBLIC COMMENT

The Board provides opportunities for public comment at its meetings. Following are highlights from public comments at the October 26, 2010, meeting.

- Get a national agreement that a repository is needed; describe the problem and how the repository solves it; deal with existing waste.
- Replacing the existing waste with new waste is a whole different conversation.

- A standard needs to be set, and zero release is a reasonable expectation for people living next to the repository.
- Incentives should be provided for people who are willing to accept a repository.
- A volunteer or a willing host will be necessary for the repository to succeed.
- In other countries, repository sites are located near other nuclear facilities.



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