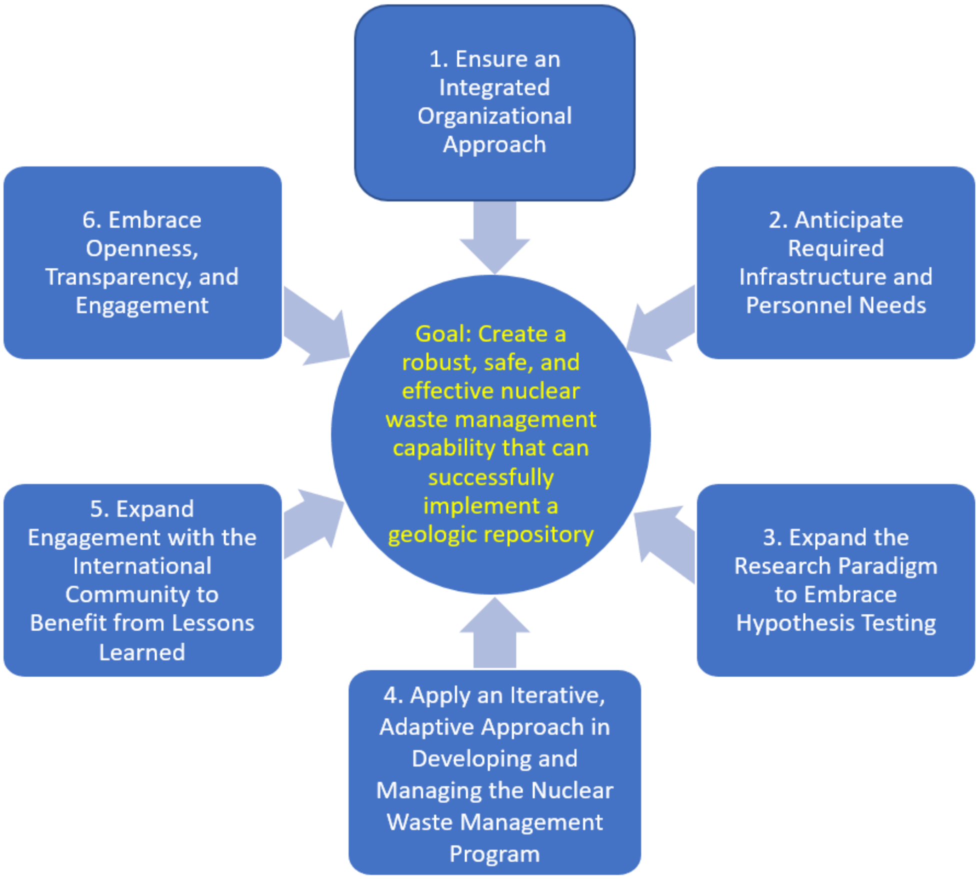
U.S. Nuclear Waste Technical Review Board

A Report to the U.S. Congress
and the Secretary of Energy

Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward



April 2021

U.S. Nuclear Waste Technical Review Board

SIX OVERARCHING RECOMMENDATIONS FOR HOW TO MOVE THE NATION'S NUCLEAR WASTE MANAGEMENT PROGRAM FORWARD

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and the Secretary of Energy

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U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

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UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3367

April 2021

The Honorable Nancy Pelosi
Speaker
United States House of Representatives
Washington, DC 20515

The Honorable Patrick J. Leahy
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable Jennifer Granholm
Secretary
U.S. Department of Energy
Washington, DC 20585

Dear Speaker Pelosi, Senator Leahy, and Secretary Granholm:

Congress created the U.S. Nuclear Waste Technical Review Board in the 1987 Nuclear Waste Policy Amendments Act (NWPAA) (Public Law 100-203) to evaluate the technical and scientific validity of activities undertaken by the Secretary of Energy to manage and dispose the nation's spent nuclear fuel (SNF) and high-level radioactive waste (HLW). In accordance with this mandate, the current Board members have synthesized their nearly decade-long experience reviewing the U.S. Department of Energy's (DOE's) activities related to the management and disposal of SNF and HLW. Our synthesis is presented in this report to Congress and the Secretary of Energy titled *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward*.

Although studies have shown that nuclear waste can be safely stored for an extended period of time if associated recommendations and programs are followed, timely progress toward the long-term solution — disposal in an underground geologic repository — is still a matter of urgency. The lack of a route for permanent disposal of SNF and HLW is one of the major impediments to the nation's further development of nuclear energy and advancement of U.S. nuclear technology and commerce. The lack of progress on developing and operating a geologic repository also impedes the associated potential benefits of having nuclear energy as part of a zero-carbon future for mitigation of climate change.

Several significant challenges need to be addressed to ensure development of a successful nuclear waste management program in the United States. These challenges include the current lack of a plan for developing a repository and concomitant funding, the complex array of stakeholders responsible for implementing different stages of the nuclear fuel cycle, and the unprecedentedly long time-scale over which a repository must be designed to protect the health and safety of the public and the environment. In this report, the Board members offer high-level recommendations to DOE which, if adopted as core principles, will support the creation of a robust, safe, and effective nuclear waste management capability for the nation, including laying the groundwork for a successful geologic repository.

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Based on the information developed in the report, the Board members provide the following six overarching recommendations and associated action items:

1. ***Ensure an Integrated Organizational Approach***

   - *Foster broader sharing of information among DOE offices, national laboratories, and contractors (e.g., university researchers supported by Nuclear Energy University Program grants).*
   - *Further enhance integration of research and development (R&D) programs executed by DOE's Office of Environmental Management, Office of Nuclear Energy, and other DOE offices to optimize collaboration, minimize duplication, and maximize the effectiveness of the effort.*
   - *Find ways to work with utilities, cask vendors, fuel manufacturers, and others in the nuclear industry in an ongoing manner, to more effectively develop and implement the nuclear waste management program.*
   - *Find additional innovative ways of information sharing through DOE-led conferences or workshops that might encourage the different entities in the implementation matrix in Table 3-1 of the report to improve communications and engagement.*

2. ***Anticipate Required Infrastructure and Personnel Needs***

   - *Develop and communicate an integrated plan regarding physical infrastructure, information technology, and personnel needs over the next decade.*
   - *Formulate and implement research programs and other supporting infrastructure consistently to anticipate the effects of aging of facilities.*
   - *Develop and maintain the capability to utilize DOE's leading-edge, high-performance computing resources for the analysis and simulation of processes and systems related to the back-end of the fuel cycle.*
   - *Develop infrastructure for and implement data management systems that can meet the needs for long-term, open, and efficient retrieval of information from current and, to the extent possible, previous relevant R&D programs.*
   - *Address the challenges of an aging workforce by expanding mentorship of a new generation of staff through: technical training programs; more effectively targeting undergraduate scholarships, graduate fellowships, and post-doctoral fellowships in areas of need; establishing internships at underground research laboratories (URLs); and promoting careers in nuclear waste management as an opportunity to address this grand environmental challenge.*

3. ***Expand the Research Paradigm to Embrace Hypothesis Testing***

   - *Anticipate surprises or unexpected results that may arise during the R&D program and assure all research programs include ample provisions to accommodate possible changes in direction and focus.*
   - *Test alternative hypotheses using careful experimental design over multiple scales from laboratory to full-scale in-situ tests in a URL.*
   - *Continue to make new measurements to build a database that tests the abilities of existing models to capture important processes and evaluate the possible need for new conceptual models to improve estimates of system properties and thus prediction accuracy.*
   - *Use results of repeated testing of existing and evolving hypotheses to enhance the usefulness of models in performance assessment.*

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- *Establish one or more dedicated domestic URLs that will provide the necessary opportunities for researchers and students to conduct in-situ investigations into subsurface processes at scale, test models, and further international collaboration.*

4. ***Apply an Iterative, Adaptive Approach in Developing and Managing the Nuclear Waste Management Program***
   - *Iterate between testing individual components of the nuclear waste management program and testing integrated models of the entire waste management system, always being ready to adapt each approach based on what is learned from such testing.*
   - *Be open and structured to adapt to surprises during all aspects of the nuclear waste management program and always be willing to reevaluate and rethink previous decisions.*
   - *Establish mechanisms as part of on-going evaluations to facilitate and incentivize solicitation of input and feedback from all affected stakeholders, including: independent scientists and engineers outside of the nuclear waste management program; local, state, and tribal governments; nuclear utilities; and the interested public.*
5. ***Expand Engagement with the International Community to Benefit from Lessons Learned***
   - *Build on current initiatives and continue to expand engagement with the international community, recognizing the need for global cooperation in science and technology in this world-wide grand environmental challenge.*
   - *Sustain active engagement in international programs given the tangible benefits derived from close involvement.*
   - *Continue and expand participation in collaborative international URL activities. If, as recommended in Section 4.3 of the report, DOE develops one or more URLs, it should encourage international participation, which could benefit the DOE program by incorporating broader perspectives and expertise.*
   - *Emphasize engagement with countries that have advanced to the demonstration and/or construction authorization stages of repository development to enhance knowledge of these stages.*
6. ***Embrace Openness, Transparency, and Engagement***
   - *Inform and engage the public and other affected stakeholders early in the planning and review of all aspects of the nuclear waste management program.*
   - *Be transparent in decision-making and provide support for meaningful stakeholder participation.*
   - *Take account of lessons learned in other countries about listening to and informing the public, in order to improve communications, better understand community perspectives, and avoid unnecessary delays of the program.*
   - *Though not a license requirement for any new site selected for a repository, DOE should develop and make available a clear characterization of the facility early in the process that describes the waste management concept and its multiple barriers and other attributes that contribute to safety. DOE must also clearly acknowledge and communicate its commitment that the safety concept will be revised to update it as new information and input are received.*
   - *Develop site-suitability criteria prior to the start of site selection so as to minimize any ambiguity and latitude in their interpretation, thus helping to ensure the objectivity of the process and*

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public confidence in its outcome. If, at any point during the siting process, the criteria need to be changed, a transparent and meaningfully participatory process to do so needs to be followed.

- *If, as recommended in Section 4.3 of the report, the United States develops one or more URLs, these laboratories, in addition to their research function, should be utilized for outreach and public engagement, in order to provide access to the subsurface (a vague concept with the public) and to build public confidence and trust in the science and engineering behind the safety concept, as well as in the operational capabilities for remote handling of waste underground.*

The Board trusts that Congress and the Secretary will find the information in this report useful and looks forward to continuing its ongoing technical and scientific review of DOE activities related to nuclear waste management and disposal.

Sincerely,

{signed}

Jean M. Bahr
Chair

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Figures, Tables, and Boxes

Figures

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Boxes

ABBREVIATIONS AND ACRONYMS

Andra	Agence nationale pour la gestion des déchets radioactifs (National Radioactive Waste Management Agency), France
APM	Adaptive Phased Management, Canada's plan for long-term management of spent nuclear fuel
ASN	Autorité de sûreté nucléaire (Nuclear Safety Authority), France
BEIS	Department for Business, Energy and Industrial Strategy, United Kingdom
BGE	Bundesgesellschaft für Endlagerung mbH (Federal Company for Radioactive Waste Disposal), Germany
BMU	Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Federal Ministry for Environment, Nature Conservation and Nuclear Safety), Germany
BRC	Blue Ribbon Commission on America's Nuclear Future
DECOVALEX	DEvelopment of COupled Models and their VALidation Against Experiments
DOE	U.S. Department of Energy
DOE-EM	U.S. Department of Energy, Office of Environmental Management
DOE-NE	U.S. Department of Energy, Office of Nuclear Energy
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute, USA
FE	Full-scale Emplacement experiment, Mont Terri URL, Switzerland
GAO	U.S. Government Accountability Office
HLW	high-level radioactive waste
HYDROCOIN	HYDROlogic COde INtercomparison
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory, USA
INTRACOIN	International Nuclide TRAnsport COde INtercomparison
MITYC	Ministerio de Industria, Turismo y Comercio (Ministry of Industry, Tourism and Commerce), Spain
MOEF	Multi-Objective Evaluation Framework
MTHM	metric ton of heavy metal
Nagra	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (National Cooperative for the Disposal of Radioactive Waste), Switzerland
NEA	Nuclear Energy Agency, Organization for Economic Co-operation and Development, France
NGSAM	Next Generation System Analysis Model
NRC	U.S. Nuclear Regulatory Commission
NUMO	Nuclear Waste Management Organization, Japan
NWMO	Nuclear Waste Management Organization, Canada
NWPA	Nuclear Waste Policy Act
NWTRB	U.S. Nuclear Waste Technical Review Board (Board)
OMB	Office of Management and Budget
ONDRAF	Organisme national des déchets radioactifs et des matières fissiles enrichies (National Organization for Radioactive Waste and Enriched Fissile Materials), Belgium

R&D	research and development
RWM	Radioactive Waste Management, United Kingdom
SFOE	Swiss Federal Office of Energy, Switzerland
SFWMD	South Florida Water Management District, USA
SKB	Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management), Sweden
SNF	spent nuclear fuel
SNL	Sandia National Laboratories, USA
SRS	Savannah River Site, USA
SSM	Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority), Sweden
START	Stakeholder Tool for Assessing Radioactive Transportation
STUK	Säteilyturvakeskus (Radiation and Nuclear Safety Authority), Finland
TRAGIS	Transportation Routing Analysis Geographic Information System
UNF-ST&DARDS	Used Nuclear Fuel Storage, Transportation & Disposal Analysis Resource and Data System
URL	underground research laboratory
USACE	U.S. Army Corps of Engineers
WIPP	Waste Isolation Pilot Plant, New Mexico, USA

Executive Summary

The goal of this report is to communicate high-level recommendations to the U.S. Department of Energy (DOE), which if adopted, the U.S. Nuclear Waste Technical Review Board (Board) members believe will support the creation of a robust, safe, and effective nuclear waste management capability for the nation, including laying the groundwork for a successful geologic repository. The DOE nuclear waste management program encompasses the management and disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW), in addition to the packaging and transportation of SNF and HLW, as well as issues arising from on-site storage of commercial SNF that could affect those activities. Our recommendations and associated action items emphasize the knowledge gained by the current Board members over the last decade reviewing numerous DOE technical programs. They are also informed by the study of and a number of visits to programs and facilities in other countries. The recommendations made in this report are focused on addressing overarching aspects of how the nuclear waste management program is performed and communicated, rather than on individual projects. We strongly believe the progress the nation is making in developing its waste management capability, as well as public and stakeholder acceptance, could be improved with regard to both timeliness and effectiveness by adopting these recommendations as core principles of the nuclear waste management program.

Current Situation

The United States has accumulated one of the largest inventories of SNF in the world, from both the operation of commercial nuclear power plants and government operations related to research and development (R&D) and defense programs, with the commercial inventory continuing to grow. In addition, there is a large inventory of government HLW, derived mainly from defense programs, with some stored as liquid in tanks and the remainder encapsulated in glass. Studies have shown that SNF and HLW can be safely stored on the surface for an extended period of time if associated recommendations and programs are followed, such as processing liquid HLW stored in underground tanks to a vitrified waste form. However, timely progress toward the long-term solution — disposal in an underground geologic repository — is still required as the lack of a solution to dispose of existing radioactive waste is costly and one of the major impediments to the nation's further development of nuclear energy. The lack of progress on developing and operating a geologic repository also impedes the associated potential benefits of having nuclear energy as part of a zero-carbon future for mitigation of climate change as well as the advancement of U.S. nuclear technology and commerce. Historically the U.S.'s world-wide leadership in nuclear technology has been important to influence non-proliferation and nuclear safety standards globally. Generational equity also calls for timely progress on implementing a geologic repository.

Challenges to Making R&D Progress

There are numerous daunting challenges to making progress on the R&D required to enable advancement of waste management capabilities. Since extended monitoring of a geologic repository after closure is currently not possible, and waste retrieval from a geologic repository is extremely difficult, forecasts of repository behavior are needed for time periods that could extend to one million years as the basis for designing and licensing a repository. The scientific and technical challenge of making such forecasts over a time scale where significant geological and human behavior changes can occur is truly a grand environmental challenge. Adding to the challenge of making R&D progress are two other factors, one being the lack of a national plan for how to move forward in developing a nuclear waste management program, which diffuses the focus of R&D. The other challenge is the organizational complexity derived from the number of entities in the United States involved in nuclear energy on the commercial side, where responsibility for nuclear power plant operations and SNF storage lies with the nuclear utilities, and responsibility for SNF transportation and disposal lies with the government. This organizational complexity affects the entire waste management system because steps taken in the earlier operational stages impact the later operational stages. This can be contrasted with countries making real progress toward implementing a geologic repository, such as Finland, Sweden and, to some extent, France, where one entity oversees or strongly influences all these operational stages.

Overarching Recommendations and Associated Action Items

In this report, we offer six interrelated, overarching recommendations that paint an integrated vision for how to move the nuclear waste management program forward, even though there is currently no plan for developing a repository. The adoption of these recommendations as core principles by DOE could help guide efforts to develop and implement a successful waste management program in the nation. This report does not present an exhaustive tabulation of all the Board's recommendations published in the past years, but rather a set of strategies to aid DOE (and to inform Congress) as the nation considers its efforts to dispose of nuclear waste. The six recommendations, presented in Figure ES-1, are put forth to facilitate the timely and effective implementation of a successful nuclear waste management program in support of developing a geologic repository. The first two recommendations deal with the design and effective operation of an integrated nuclear waste management program under DOE. The next two recommendations provide guidance on creating a more effective and rigorous science and engineering program. The final two recommendations deal with building public trust and international engagement to foster success in the program.

Associated with each recommendation is a set of action items (see Table ES-1 below). The Board recognizes that some of the action items identified here require important contributions from entities that are beyond DOE's control and require both authorization and appropriations by Congress. Nonetheless, we offer some specific actions intended to help DOE turn the recommendations into core principles for developing the nuclear waste management program, including the successful development of a geologic repository.

Implementation of many of these actions can be accomplished by DOE in the near term but could also be continued by a new implementer in the future, if that is the course taken by policy makers. Regardless, adopting our recommendations will require long-term sustained commitment and efforts to maintain them as core principles of the program. In some instances, this means expanding current approaches, and in other cases it involves embracing new ways of doing business by all the organizations involved. We recognize that DOE has already made important efforts, and that embracing change can be challenging, especially across a complex system of entities. However, we believe not only that DOE can implement many of these shifts

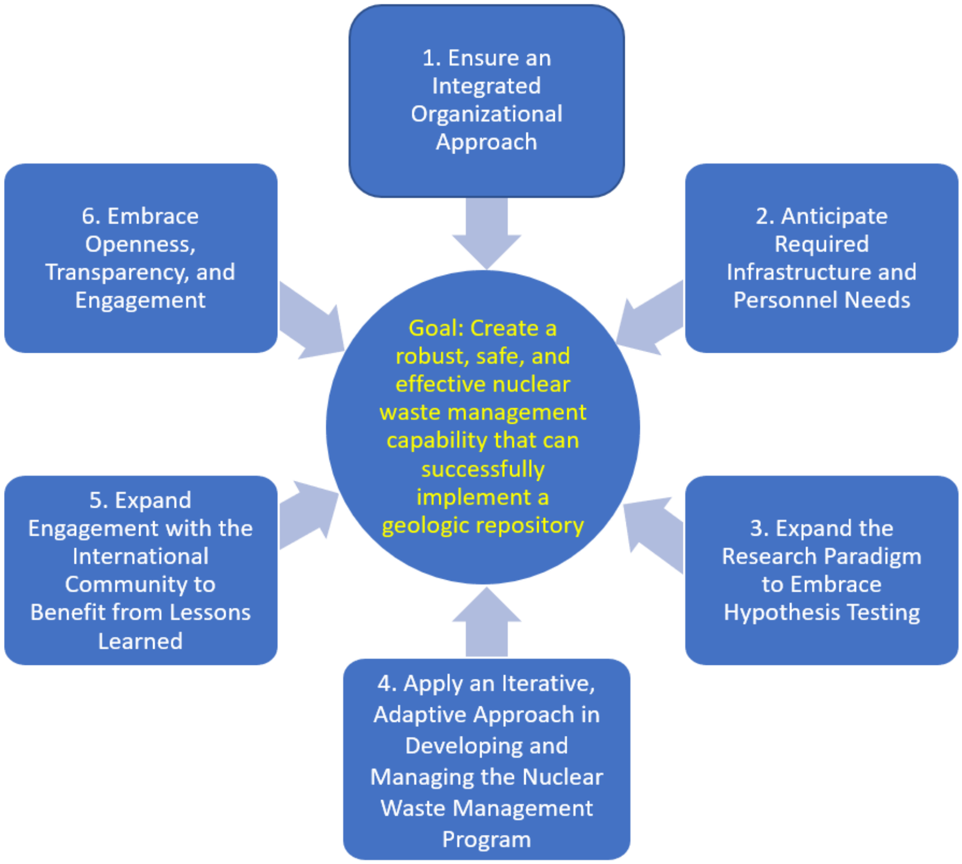

Figure ES-1. Six overarching recommendations for DOE's nuclear waste management program in support of developing a successful geologic repository program in the United States.

in effort now but that such implementation is crucial if the nation is to make timely progress on a nuclear waste management program in support of developing a geologic repository to effectively address the nuclear waste issue.

Table ES-1. Board Recommendations and Associated Action Items for DOE's Nuclear Waste Management Program
1. Ensure an Integrated Organizational Approach • Foster broader sharing of information among DOE offices, national laboratories, and contractors (e.g., university researchers supported by Nuclear Energy University Program grants). • Further enhance integration of R&D programs executed by DOE's Office of Environmental Management, Office of Nuclear Energy, and other DOE offices to optimize collaboration, minimize duplication, and maximize the effectiveness of the effort. • Find ways to work with utilities, cask vendors, fuel manufacturers, and others in the nuclear industry in an ongoing manner, to more effectively develop and implement the nuclear waste management program. • Find additional innovative ways of information sharing through DOE-led conferences or workshops that might encourage the different entities in the implementation matrix in Table 3-1 to improve communications and engagement.
2. Anticipate Required Infrastructure and Personnel Needs • Develop and communicate an integrated plan regarding physical infrastructure, information technology, and personnel needs over the next decade. • Formulate and implement research programs and other supporting infrastructure consistently to anticipate the effects of aging of facilities. • Develop and maintain the capability to utilize DOE's leading-edge, high-performance computing resources for the analysis and simulation of processes and systems related to the back-end of the fuel cycle. • Develop infrastructure for and implement data management systems that can meet the needs for long-term, open, and efficient retrieval of information from current and, to the extent possible, previous relevant R&D programs. • Address the challenges of an aging workforce by expanding mentorship of a new generation of staff through: technical training programs; more effectively targeting undergraduate scholarships, graduate fellowships, and post-doctoral fellowships in areas of need; establishing internships at underground research laboratories (URLs); and promoting careers in nuclear waste management as an opportunity to address this grand environmental challenge.
3. Expand the Research Paradigm to Embrace Hypothesis Testing • Anticipate surprises or unexpected results that may arise during the R&D program and assure all research programs include ample provisions to accommodate possible changes in direction and focus. • Test alternative hypotheses using careful experimental design over multiple scales from laboratory to full-scale in-situ tests in a URL. • Continue to make new measurements to build a database that tests the abilities of existing models to capture important processes and evaluate the possible need for new conceptual models to improve estimates of system properties and thus prediction accuracy. • Use results of repeated testing of existing and evolving hypotheses to enhance the usefulness of models in performance assessment. • Establish one or more dedicated domestic URLs that will provide the necessary opportunities for researchers and students to conduct in-situ investigations into subsurface processes at scale, test models, and further international collaboration.

Table ES-1. Board Recommendations and Associated Action Items for DOE's Nuclear Waste Management Program (Continued)

4. Apply an Iterative, Adaptive Approach in Developing and Managing the Nuclear Waste Management Program

- Iterate between testing individual components of the nuclear waste management program and testing integrated models of the entire waste management system, always being ready to adapt each approach based on what is learned from such testing.
- Be open and structured to adapt to surprises during all aspects of the nuclear waste management program and always be willing to reevaluate and rethink previous decisions.
- Establish mechanisms as part of on-going evaluations to facilitate and incentivize solicitation of input and feedback from all affected stakeholders, including: independent scientists and engineers outside of the nuclear waste management program; local, state, and tribal governments; nuclear utilities; and the interested public.

5. Expand Engagement with the International Community to Benefit from Lessons Learned

- Build on current initiatives and continue to expand engagement with the international community, recognizing the need for global cooperation in science and technology in this world-wide grand environmental challenge.
- Sustain active engagement in international programs given the tangible benefits derived from close involvement.
- Continue and expand participation in collaborative international URL activities. If, as recommended in Section 4.3, DOE develops one or more URLs, it should encourage international participation, which could benefit the DOE program by incorporating broader perspectives and expertise.
- Emphasize engagement with countries that have advanced to the demonstration and/or construction authorization stages of repository development to enhance knowledge of these stages.

6. Embrace Openness, Transparency, and Engagement

- Inform and engage the public and other affected stakeholders early in the planning and review of all aspects of the nuclear waste management program.
- Be transparent in decision-making and provide support for meaningful stakeholder participation.
- Take account of lessons learned in other countries about listening to and informing the public, in order to improve communications, better understand community perspectives, and avoid unnecessary delays of the program.
- Though not a license requirement for any new site selected for a repository, DOE should develop and make available a clear characterization of the facility early in the process that describes the waste management concept and its multiple barriers and other attributes that contribute to safety. DOE must also clearly acknowledge and communicate its commitment that the safety concept will be revised to update it as new information and input are received.
- Develop site-suitability criteria prior to the start of site selection so as to minimize any ambiguity and latitude in their interpretation, thus helping to ensure the objectivity of the process and public confidence in its outcome. If, at any point during the siting process, the criteria need to be changed, a transparent and meaningfully participatory process to do so needs to be followed.
- If, as recommended in Section 4.3, the United States develops one or more URLs, these laboratories, in addition to their research function, should be utilized for outreach and public engagement, in order to provide access to the subsurface (a vague concept with the public) and to build public confidence and trust in the science and engineering behind the safety concept, as well as in the operational capabilities for remote handling of waste underground.

1.0 INTRODUCTION

1.1 Purpose and Scope

The role of the U.S. Nuclear Waste Technical Review Board (NWTRB or Board) as defined in the Nuclear Waste Policy Amendments Act (Title V of Public Law 100-203; U.S. Congress 1987) is to "…evaluate the technical and scientific validity of activities undertaken by the Secretary [of Energy] after the date of the enactment of the Nuclear Waste Policy Amendments Act of 1987 [enacted Dec. 22, 1987], including (1) site characterization activities; and (2) activities relating to the packaging or transportation of high-level radioactive waste or spent nuclear fuel." Those activities undertaken by the Secretary include the U.S. Department of Energy's (DOE's) management and disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW), in addition to the packaging and transportation of SNF and HLW, as well as issues arising from on-site storage that could affect those activities. **Collectively, all of these DOE activities will be referred to as "the nuclear waste management program" throughout this report.** Most of the current Board members were appointed in 2012 and, thus, have nearly a decade of experience reviewing DOE activities and how they contribute to meeting the grand scientific and technological challenge of managing and permanently disposing of nuclear waste in the United States. The Board members also have had opportunities to observe and learn from waste management programs in other countries that are facing a similar challenge. Through this experience, the Board members have seen the complex interplay between technical issues and societal and institutional factors that affect progress towards implementing a successful geologic repository program (NWTRB 2011, 2015a, 2016a).

Like others who have reported on the U.S. nuclear waste management program (e.g., National Research Council 1992, 1995a, 1995b, 2006), the Board has generally written separate reports on specific and focused technical topics, while advocating for an improved and integrated program for the storage, transportation, and disposal of nuclear waste in the United States. Along with many other organizations, the Board also recognizes that there are huge challenges to solving the U.S. waste problem; notably, the unprecedented time-scale required of the solution, the current lack of a plan for developing a repository and concomitant funding, as well as a complex matrix of stakeholders owning different parts of the solution. The goal of this report is to provide high-level recommendations to DOE, which if adopted as core principles, will support the creation of a robust, safe, and effective nuclear waste management capability and lay the groundwork for a successful geologic repository. This report offers six integrating and overarching recommendations for DOE to consider now to enhance the effectiveness of its nuclear waste management program and leave it poised to move forward when decisions are made. Our recommendations would apply equally to any new entity that might be created in the future by policymakers to implement the waste management and disposal mission, as advocated in the 2012 Blue Ribbon Commission on America's Nuclear Future (BRC) Report to the Secretary of Energy (BRC 2012).

As a Board, we share the sense of urgency expressed nine years ago by the bipartisan co-chairs of the BRC — Representative Lee Hamilton and General Brent Scowcroft. For example, in their cover letter to the BRC report, they wrote:

"We approached our task from different perspectives but with a shared sense of urgency. Put simply, this nation's failure to come to grips with the nuclear waste issue has already proved damaging and costly. It will be even more damaging and more costly the longer it continues: damaging to prospects for maintaining a potentially important energy supply option for the future, damaging to state–federal relations and public confidence in the federal government's competence, and damaging to America's standing in the world—not only as a source of nuclear technology and policy expertise but as a leader on global issues of nuclear safety, non-proliferation, and security."

In addition to sharing the concerns that the BRC co-chairs described so well, we note that today, in 2021, there is a much more urgent imperative to address climate change for which nuclear energy could play a part. The lack of a national plan for developing a nuclear waste management program impedes development of nuclear energy as part of a zero-carbon energy future for addressing climate change. Furthermore, generational equity speaks to urgency. As SKB, the implementer of Sweden's nuclear waste management program, states (SKB 2021a):

"Our generation must take care of the Swedish nuclear waste…We who have benefited from this electricity also have a responsibility to future generations to deal with the waste it has given rise to."

The impediments and constraints to solving the U.S. waste problem are significant. In Sections 2 and 3, we briefly discuss the technical, political, and legislative, as well as the organizational constraints and impediments to making progress on permanent disposal of the waste. We recognize that DOE does not have the freedom to manage the U.S. program independently; it is constrained by limits on its funding and authorization, by contractual obligations and by other actors and influences that have a major impact on how the nuclear waste management program evolves. Consequently, DOE's ability to implement some of our recommendations will depend on funding, actions, and decisions emanating from other entities such as Congress, the U.S. Nuclear Regulatory Commission (NRC), and the nuclear industry. This Board nonetheless strongly believes that DOE can further enhance the effectiveness of its work related to storage, transportation, and disposal by implementing recommendations herein as the foregoing constraints permit.

In addition to the Board's publications, five primary sources have informed this report: (1) reviews of DOE work based on presentations by DOE and national laboratory staff and by non-DOE experts at Board public meetings, (2) published literature, including DOE reports and peer-reviewed articles, (3) site visits to laboratories and facilities, (4) fact-finding missions by small Board and staff teams to address particular technical and scientific issues, and (5) international trips to Belgium, China, France, Sweden, and Switzerland to directly observe nuclear waste management facilities and meet with program leaders and, in some cases, the public. Our recommendations are grounded in technical work by the Board. However, these recommendations build upon and go beyond the Board's individual reports and the specific findings in those reports.

Finally, we also recognize that DOE has previously identified many of the same issues that we highlight here (e.g., Rechard et al. 2010). Likewise, many of these issues have been discussed previously by other entities (e.g., Bowen 2021) and were mentioned in the BRC report (BRC 2012) or in DOE's response to that report (DOE 2013). Nonetheless, if these high-level recommendations are adopted by DOE, we believe they will support the creation of a robust, safe, and effective nuclear waste management capability for the nation, including laying the groundwork for a successfully implemented geologic repository. We believe our recommendations are essential to forward movement within today's environment of rapid technical, political, and social change.

1.2 The Scale of the Problem: U.S. Inventory of Spent Nuclear Fuel and High-Level Radioactive Waste

The U.S. inventory of nuclear waste ranks among the largest and most diverse on the globe. The inventory, including SNF and HLW, is a result of the world's largest number of commercial nuclear power plants and the DOE weapons programs and national security and research missions. Figure 1-1 shows the estimated volumes of different solid waste types requiring geologic disposal based on the SNF and HLW inventory as of 2012 and the inventory projected through 2048 (NWTRB 2017a). As Figure 1-1 depicts, commercial SNF comprises the vast

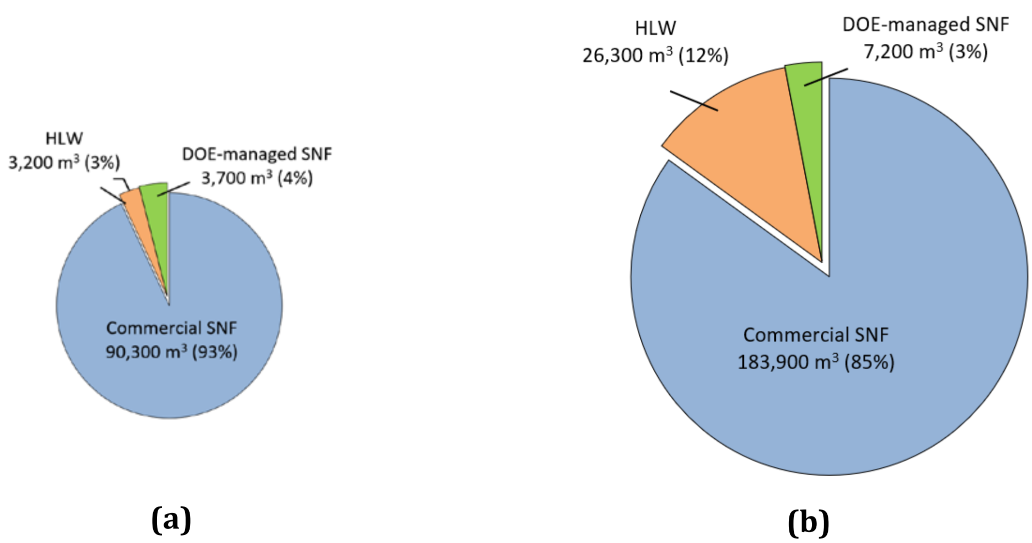

Figure 1-1. Estimated volumes of different waste forms requiring geologic disposal based on the inventory of U.S. spent nuclear fuel and high-level radioactive waste as of 2012 (a) and projected to 2048 (b).[1]

[1] Data from SNL (2014). The estimated waste form volumes in SNL (2014) are based on the inventory of commercial SNF existing as of 2012 and on several assumptions, including (1) commercial nuclear power generation remains unchanged from today's rate and all commercial SNF is eventually packaged in dual-purpose canisters, (2) sodium-bonded fuels undergo electrometallurgical treatment, (3) calcined HLW is processed by hot isostatic pressing, and (4) all other HLW (including the cesium and strontium currently stored in capsules) is vitrified. Much of the existing HLW remains unprocessed and stored as liquid in underground tanks at the Savannah River Site (SRS) and the Hanford Site. The HLW in underground tanks will be vitrified. Some of the other types of HLW will be solidified using different technologies. For brevity in this report, all solidified HLW is referred to as vitrified HLW.

majority of the U.S. waste requiring geologic disposal. The commercial SNF inventory, managed by nuclear utilities, is generated from the operation of commercial nuclear power plants. The small volume of DOE-managed SNF mainly originated from defense and research-related activities (NWTRB 2017b). The commercial SNF dominance is significantly more when measured in terms of radioactivity. Figure 1-2 is a snapshot of the estimated radioactivity of commercial SNF and DOE-managed SNF and HLW showing that almost all the radioactivity comes from commercial SNF. Commercial SNF will continue to dominate in future years because of the continued operation of nuclear power plants.

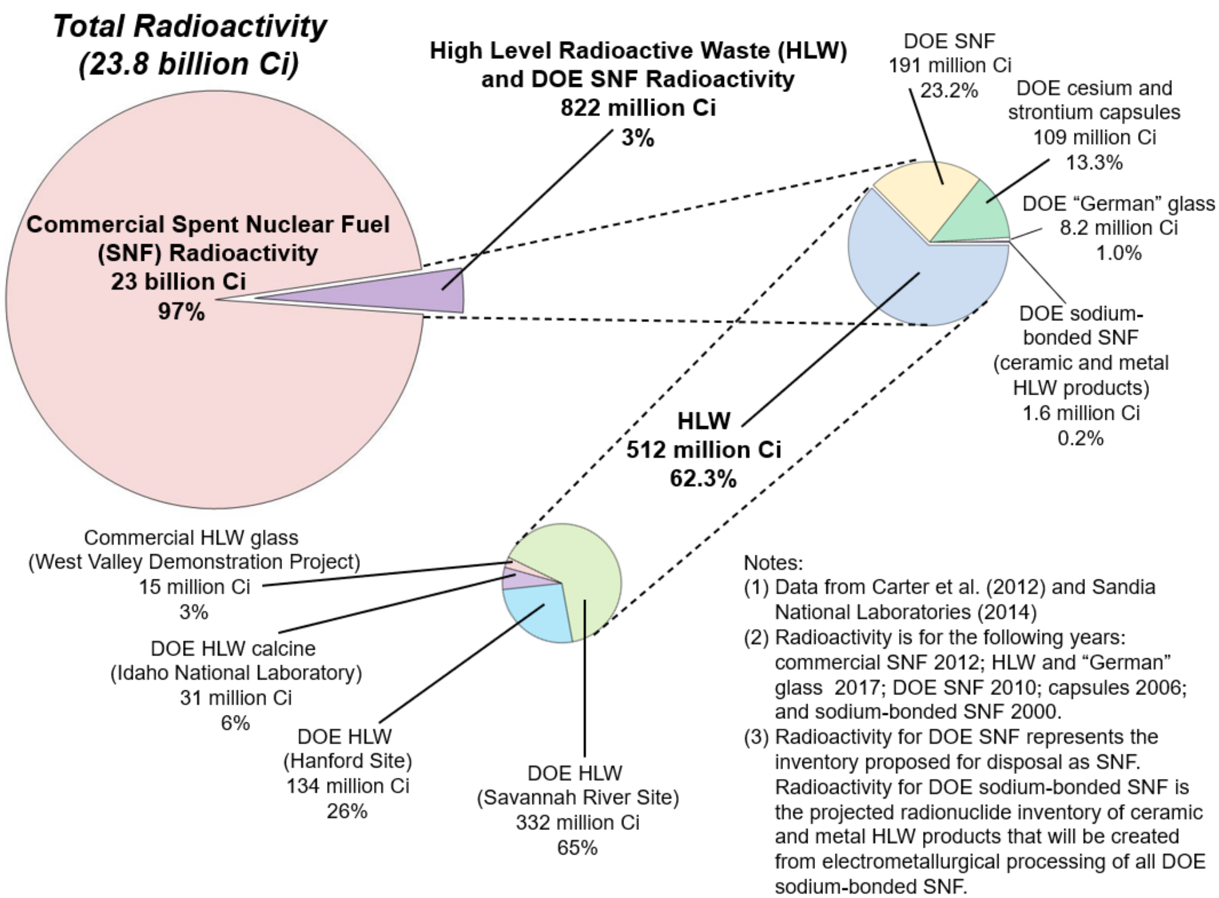

Figure 1-2. Snapshot of the radioactivity of U.S. spent nuclear fuel and high-level radioactive waste.[2]

[2] Figure modified from NWTRB (2017b). The radioactivity emitted by SNF (in curies, Ci) comes from commercial SNF and DOE-managed SNF. The radioactivity emitted by HLW comes from the cesium and strontium capsules stored at the Hanford Site; 34 canisters of glass, also stored at the Hanford Site, created by DOE in the late 1980s in support of the HLW disposal program in Germany; 275 HLW glass canisters at West Valley, New York; the canisters of vitrified HLW at the SRS; the calcined HLW stored at the Idaho National Laboratory (INL); and the HLW currently stored as a liquid in underground tanks at SRS and the Hanford Site. DOE plans to vitrify the remaining liquid HLW at SRS and the Hanford Site in preparation for disposal.

The U.S. inventory of SNF and HLW is currently stored at 113 sites in 39 states, with approximate locations shown in Figure 1-3. More specifically, the commercial SNF is stored at 76 nuclear power plant or storage sites in 34 states, while DOE-managed SNF and HLW are stored at six DOE sites[4] (Peters et al. 2020).

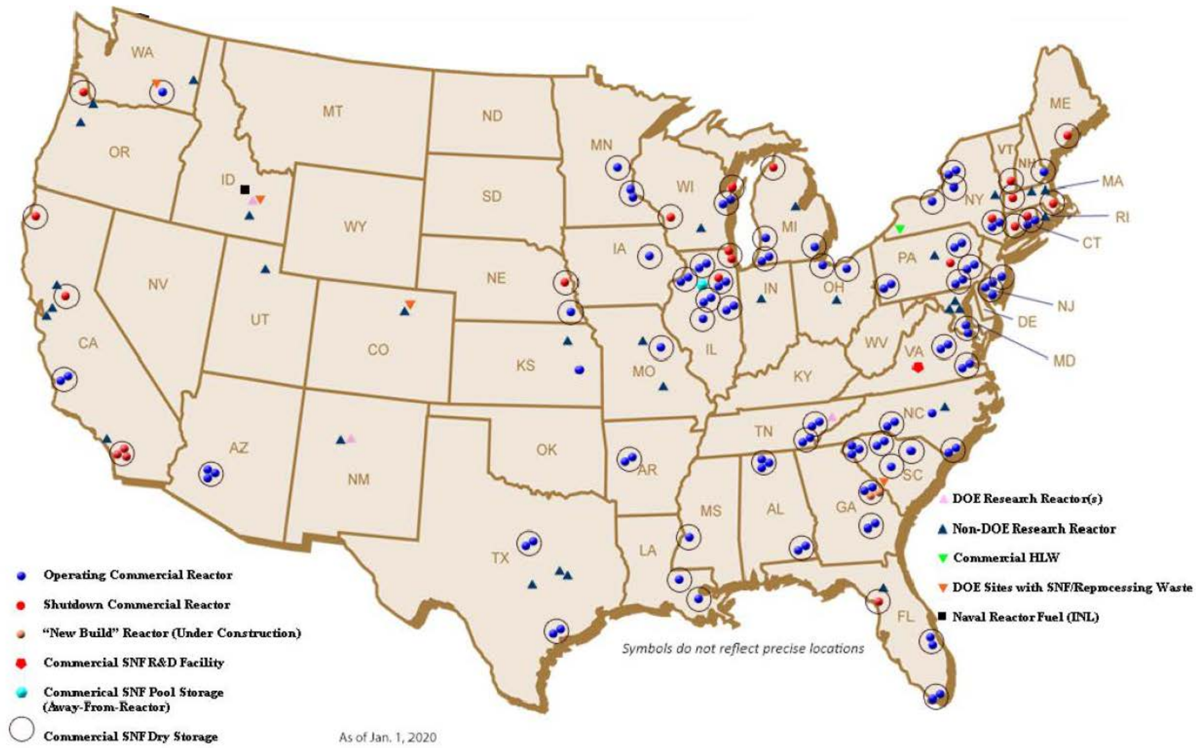

Figure 1-3. Approximate locations of sites storing U.S. spent nuclear fuel and high-level radioactive waste.[3] Note: Modified from Peters et al. (2020).

DOE-managed SNF includes a diverse collection of fuel and cladding types stored in both water-filled pools and in dry storage. Figure 1-4 shows an example of DOE-managed SNF stored under water at the L Basin building at SRS. Figure 1-5 shows examples of dry-storage systems used for commercial SNF. Some of the containers used for dry storage of SNF at commercial sites are licensed for storage and transportation, while others are only licensed for storage. Some of the HLW in tanks has been vitrified (converted to a more stable solid glass form), but more than 90% of the volume of that waste remains to be vitrified (NWTRB 2017c).

As nuclear power generation continues through the middle of the century, the total U.S. inventory of commercial SNF will continue to grow by ~2,200 metric tons of heavy metal

[3] The locations of 31 non-DOE research reactor sites are also shown, but the SNF stored at these sites is not relevant to this report.

[4] The six DOE sites are at the (1) Hanford Site in Washington State, (2) INL in Idaho, (3) SRS in South Carolina, (4) Fort St. Vrain Independent Spent Fuel Storage Installation in Colorado, (5) West Valley Demonstration Project in New York State and (6) Naval Reactors Storage Facility at INL.

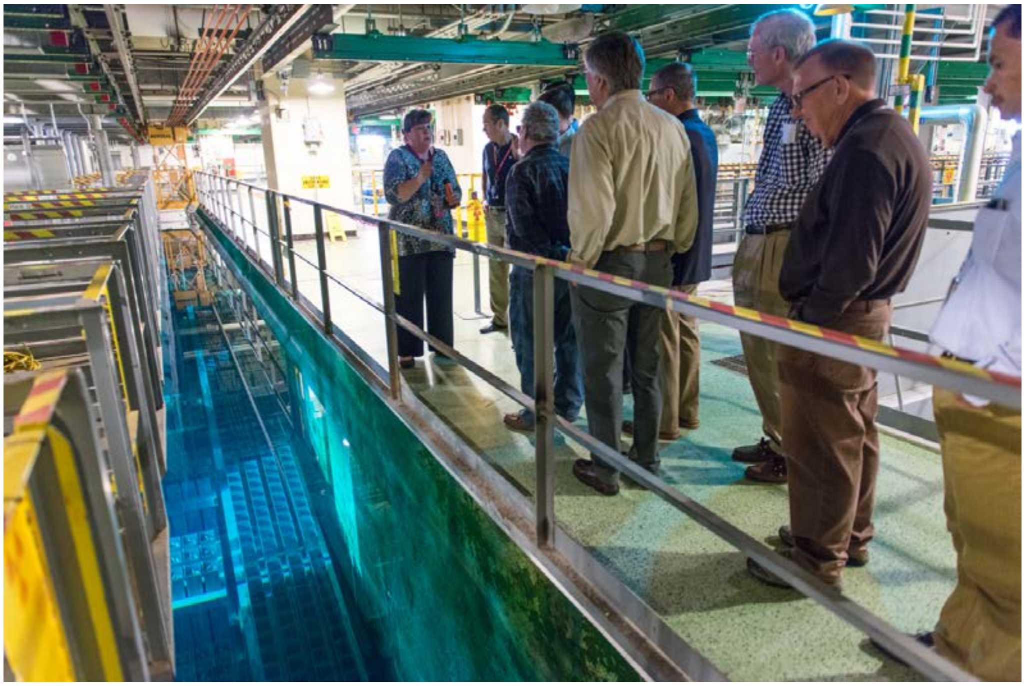

Figure 1-4. L Basin storage facility at the Savannah River Site. Vertical tube storage racks containing bundles of DOE-managed spent nuclear fuel are visible in the water-filled concrete basin. Source: NWTRB (2017b).

(a) **(b)**

Figure 1-5. (a) Horizontal and (b) vertical dry-storage systems used for commercial spent nuclear fuel. Source: NRC (2016).

(MTHM)[5] per year (Figure 1-6). As of December 2019, ~45,000 MTHM were in spent fuel pools and ~39,000 MTHM were in dry storage (Peters et al. 2020). The inventory of DOE-managed SNF also is growing, but at a much slower rate compared to the growth in inventory of commercial SNF.

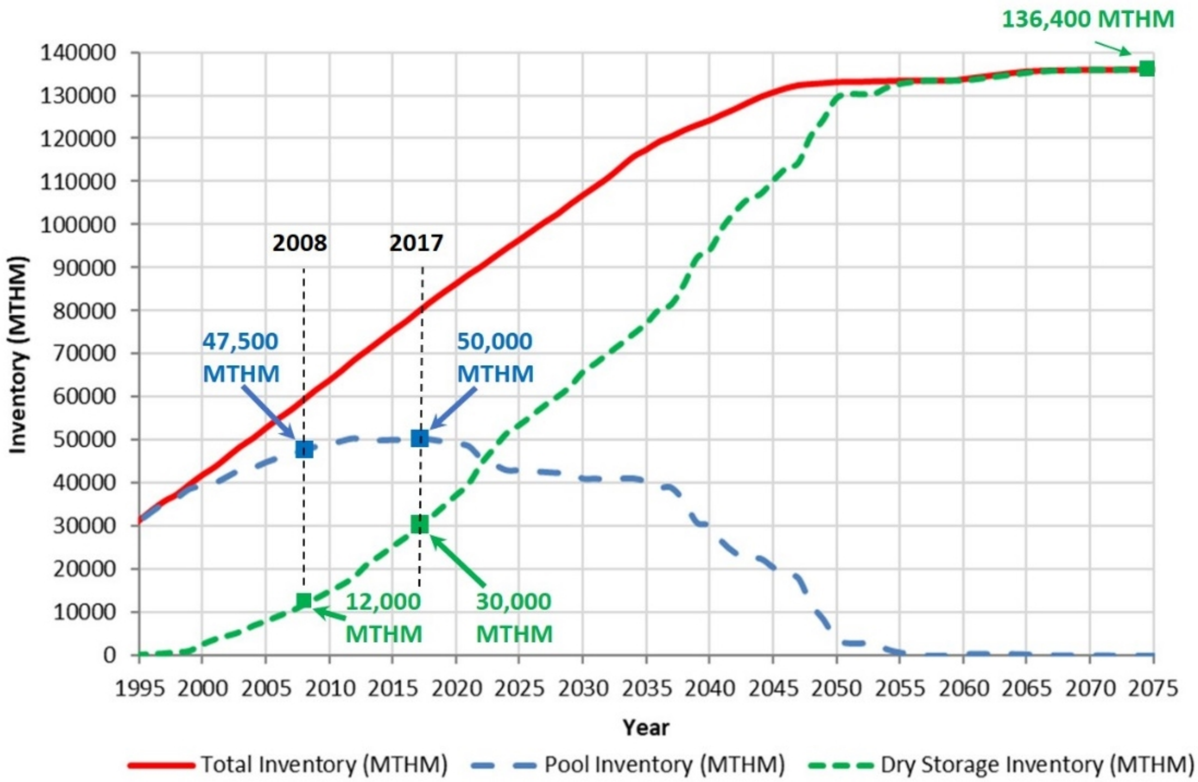

Figure 1-6. Projected inventory of commercial spent nuclear fuel (total, in spent fuel pools, and in dry storage) versus time.[6]

[5] Metric ton of heavy metal is a commonly used measure of the mass of "heavy metal" in fresh nuclear fuel. Heavy metal refers to elements with an atomic number greater than 89 (e.g., thorium, uranium, and plutonium). The masses of other constituents of the fuel, such as cladding, and structural materials, are not included. A metric ton is 1,000 kilograms, which is about 2,200 pounds.

[6] Figure taken from Freeze et al. (2019; Fig. 1-5) and revised for clarity. The projections of inventory with time developed by Vinson and Metzger (2017) and used by Freeze et al. (2019) assumed: (i) 93 of the 99 reactors operating at the end of 2017 would receive license renewals and would be decommissioned after 60 years of operation, (ii) the six existing reactors that had announced final shutdown dates as of 2017 would continue operating until those shutdown dates, (iii) no new reactors would be constructed, (iv) no commercial SNF would be reprocessed, and (v) there would be no options for permanent disposal and all commercial SNF would remain in storage. The SNF pool inventory decreases from 2017 to later years as commercial reactors cease operations and begin decommissioning, during which the SNF pools are emptied and the SNF is placed into dry storage.

2 The Challenge of Permanent Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste

Like other countries, the United States recognizes that permanent disposal of its SNF and HLW will be best accomplished in underground geologic repositories. The performance lifetimes required for these geologic repositories are the longest of any engineered design project ever attempted. Originally, the U.S. repository was to be designed to isolate waste safely for 10,000 years, but this compliance time frame was extended to one million years for the case of the Yucca Mountain repository.[7] The goal is to limit human exposure to radionuclides that may be released from the waste to acceptable levels. Other countries have set similar compliance periods between 10,000 and one million years (NWTRB 2016a, Table 7). Thus, safe disposal of nuclear waste is truly a grand environmental challenge because of the need to show that regulatory requirements adequately protect the health and safety of the public and the environment over unprecedentedly long timeframes. The enormity of this challenge cannot be overstated. Figure 2-1 places the 10,000-year compliance timeframe into context with the age of several notable human-built structures.

The necessity to isolate waste for long time frames demands that repository performance be assessed over a range of conditions that are difficult to anticipate, let alone, quantify. The science and technology challenges inherent in projection of change over such long timeframes informs all aspects of evaluating the long-term performance of the repository. For example, projections must incorporate the uncertainty associated with changes in behavior of engineered materials over unprecedently long time periods.

Such changes in engineered materials are inherently difficult to quantify, but they are even more challenging to calculate if models must take into account the possibility of future environmental and geologic changes that can occur both extremely rapidly and extremely slowly. But incorporation of future human behavior into models may be the most inherently difficult task. Recognizing this difficulty, the regulatory standard for Yucca Mountain specifies that radiation doses be calculated to assess repository performance using a stylized "reference biosphere" and the "reasonably maximally exposed individual."[8]

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[7] The U.S. Environmental Protection Agency (EPA) standards for Yucca Mountain set forth in Title 40, Part 197 (*Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada*) of the Code of Federal Regulations were issued in 2001 (EPA 2001). The 2001 standards set a dose limit of 150 microsieverts (15 millirem) per year for the first 10,000 years after disposal but did not establish a specific compliance standard for longer-term projections. After a 2004 U.S. Court of Appeals ruling, EPA amended the standards (EPA 2008) by adding a 1 millisievert (100 millirem) per year dose limit beyond 10,000 years up to 1 million years.

[8] A "reasonably maximally exposed individual" is a hypothetical person meeting the criteria specified in Title 10, Part 63.312, of the Code of Federal Regulations. The criteria include being an adult, living in the accessible environment above the highest concentration of radionuclides in the plume of contamination in groundwater, having a diet and lifestyle representative of the people in the surrounding community, and drinking a specified amount of well water. Source: https://www.nrc.gov/reading-rm/doc-collections/cfr/part063/part063-0312.html [Accessed February 3, 2021].

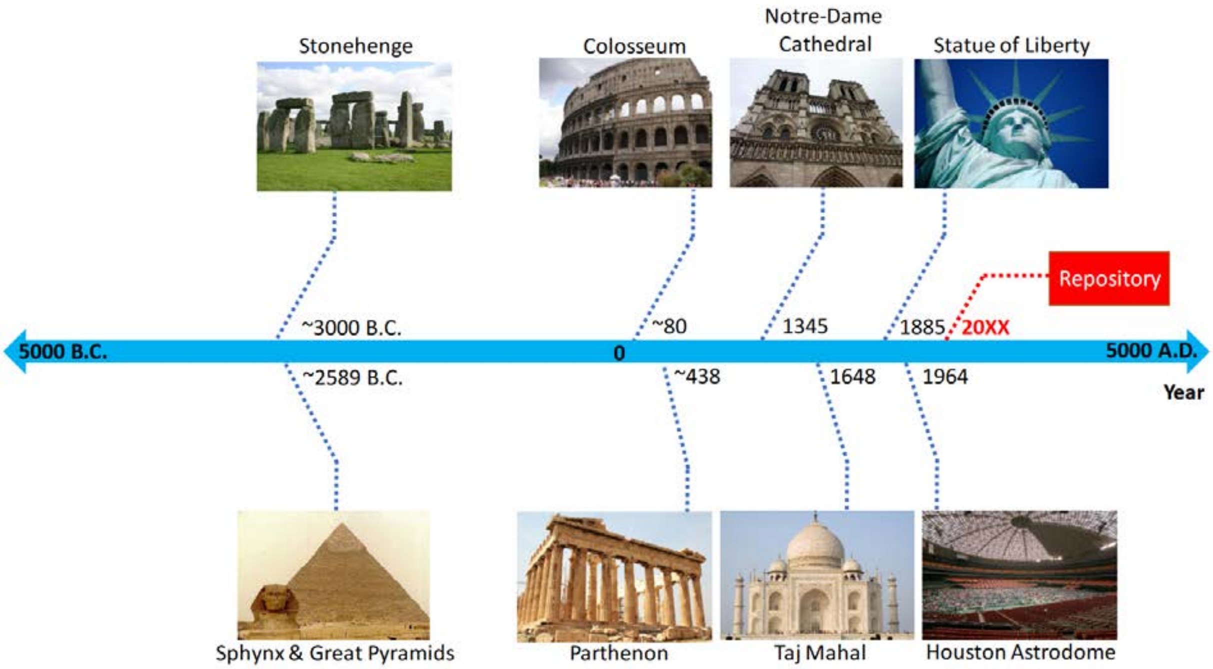

Figure 2-1. Illustration of the ages of several human-built structures compared to a 10,000-year timeframe for geologic disposal.[9]

Other countries such as Sweden (SSM 2008) and Canada (Canadian Nuclear Safety Commission 2006) have adopted similar approaches in establishing dose standards for their disposal programs. In addition to uncertainties associated with individual components of the repository system, coupling of the engineered, geological, environmental, and human systems and possible feedback loops can also affect outcomes of repository performance in ways that are difficult to model.

To project repository performance over the required timeframes, DOE must use the best science to create models of how parts of the repository system—from the waste itself to the engineered barriers to the environment itself—might change into the future. The starting point is the condition and character of waste when it is placed in a repository. However, even that baseline is difficult to assess because of the widely diverse characteristics and conditions of the waste (as discussed in Section 1.2). Furthermore, this mix of waste forms exists in a large variety of temporary modes of storage maintained for different time periods at a large number of sites around the country. The dimensions, composition, and heat load of SNF packages that will

[9] Sources: Yvonne Eijkenduijn, Stonehenge, October 8, 2006, https://flic.kr/p/pwHbo; Mike McBey, Sphynx & Great Pyramid, October 20, 2018, https://flic.kr/p/NtrvTe; Paul Morgan, Colosseum, August 8, 2005, https://flic.kr/p/jh5qQ; Steve Summers, Parthenon, April 23, 2013, https://flic.kr/p/em53vq; billandkent, Notre-Dame Cathedral, April 27, 2006, https://flic.kr/p/dqbxY; Paul Asman and Jill Lenoble, Taj Mahal, November 28, 2007, https://flic.kr/p/4hpE3D; Celso Flores, Statue of Liberty, September 21, 2009, https://flic.kr/p/7cqfD3; mad mags, Houston Astrodome, September 1, 2005, https://flic.kr/p/kxXUR. [Flickr Creative Commons accessed March 24, 2021].

eventually be disposed of will depend on decisions related to packaging and predisposal cooling that are yet to be made.

Future technological advancements in fuel composition, enrichment, and design could also create SNF that differs from SNF that is already in storage at reactor sites. In addition, the final waste form and associated characteristics are not yet fully known for some of the materials that are expected to be part of the HLW inventory, such as the large volumes of tank wastes stored at the Hanford site that are still to be vitrified. As a consequence, even before long-term modeling modules can be used reliably to project the future performance of the repository, the characteristics of the SNF and HLW at the time that disposal operations begin must be estimated.

To project repository performance into the future, models must also include forecasts of changes in the characteristics of the geologic conditions at the site. Significant advances were made in understanding how to project change in the Yucca Mountain site when it was undergoing characterization. However, DOE research on understanding long timescale changes in the geological and environmental characteristics of repository settings today is restricted to generic (i.e., non-site-specific) studies. This is because licensing and development of a repository at the Yucca Mountain site has been suspended, and no alternative repository site or the type of rock to host a repository has been chosen. Without a site, analyses can only be accomplished in a general, generic way. DOE has nonetheless been able to move forward its research by utilizing geological and archeological analogs and underground research laboratories (URLs) in other countries to develop understanding of how waste forms evolve and how aspects of the geologic environment change as a function of natural or repository-induced perturbations.

Despite the many difficult technical challenges detailed above, related to assuring safety for a geologic repository over a million-year time frame, these challenges can be met. This is evidenced by the fact that, in 2008, DOE submitted to the NRC an application for a license to construct the Yucca Mountain repository. However, in the United States, the creation of an integrated system for storage, transportation, and disposal of waste is made extremely complex by the large number of entities with responsibilities for different aspects of this system. This complex implementation matrix is discussed in the next section. Once again, it appears that it is extremely difficult to separate the purely technical problems (e.g., projecting geology forward one million years) from the sociopolitical ones (e.g., the fact that DOE is not totally in charge).

3 Constraints on the U.S. National Program

DOE is charged with "siting, construction, and operation of repositories that will provide a reasonable assurance that the public and the environment will be adequately protected from the hazards posed by high-level radioactive waste and such spent nuclear fuel as may be disposed of in a repository" as well as with transporting such waste to a repository identified in the Nuclear Waste Policy Act (NWPA) (Public Law 97-425; U.S. Congress 1982). The successful and timely execution of this mission is strongly affected by political, legislative, and institutional constraints discussed below.

3.1 The Political and Legislative Landscape

As noted in the previous section, according to international consensus, the best long-term option for dealing with SNF and HLW is disposal in a geologic repository (National Research Council 1990, 2001). However, thus far, no license authorizing the construction of an SNF and HLW repository has been issued in the United States. A site in volcanic tuff at Yucca Mountain, in southern Nevada, was selected by Congress in 2002[10] and a license application for that site was submitted by DOE to the NRC in 2008. However, in 2010, the Obama Administration determined that the proposed repository was "unworkable" and, since then, no funding has been appropriated by Congress for work to develop the repository (OMB 2011). In recent years, DOE has been conducting non-site-specific repository studies relevant to several other types of host rocks (crystalline, clay/shale, and salt). Thus, while the goal is to ultimately get the waste underground, the path forward and the likely timeline for the U.S. program remain uncertain.

One of the key requirements for DOE to be able to make meaningful progress toward transporting and disposing of SNF and HLW is maintaining a sufficient and reliable source of funding for timely planning and execution of the nuclear waste management program. The Nuclear Waste Fund was established by the NWPA and was designed to grow through income from an assessment of $0.001/kWh to be paid by the nuclear utilities for electricity generated by nuclear power (Stanford University and George Washington University 2018). Appropriations from the fund are controlled by Congress. Several budget-related laws (e.g., Gramm-Rudman-Hollings Act of 1985 and the 1990 Budget Enforcement Act) and Congressional action, led to limitations on the use of the Nuclear Waste Fund. The use of the Nuclear Waste Fund is now considered discretionary spending and subject to annual apportionment. These changes, which have made DOE funding subject to Congressional statutory and procedural limits, as well as the smaller appropriations DOE has received for its nuclear waste management program in recent years, have had a major impact in advancing the program. In 2013, a federal court decision suspended the collection of fees for the Nuclear Waste Fund by DOE "until such a time as either

[10] Congress made a "de facto" selection in 1987 in the Nuclear Waste Policy Act Amendments when Congress limited DOE's site characterization efforts to Yucca Mountain. Congress issued a more formal "selection" in 2002 by approving Yucca Mountain in *House Joint Resolution 87 —Approving the site at Yucca Mountain, Nevada, for the development of a repository for the disposal of high-level radioactive waste and spent nuclear fuel, pursuant to the Nuclear Waste Policy Act of 1982*. That legislation was then signed by then President Bush (Public Law 107-200; U.S. Congress 2002).

the secretary chooses to comply with the [Nuclear Waste Policy] Act as it is currently written, or until Congress enacts an alternative waste management plan" (Dolley and Hiruo 2013). However, interest continues to add significantly to the fund's balance. In fiscal year 2019, interest credited to the fund totaled $1.7 billion, bringing the fund's unspent balance to $40.9 billion.[11]

A second key challenge for DOE is to define and articulate a program that can gain public support. The 1987 amendment to the NWPA directed DOE to characterize the site at Yucca Mountain as a potential permanent repository and to cease work on the other two sites that were under consideration at that time. This continues to be the federal law. However, DOE has not been funded to pursue work on the Yucca Mountain repository since 2010. This led to the current uncertainty in the nation's nuclear waste management program.

In the view of the current Board, the way forward depends on the following:

- Development of a defined national plan and a timetable for developing a repository.
- Development of an integrated program for packaging, storage, transportation, and disposal.
- Availability of the necessary funding on the required timescale.
- Retention of key personnel and recruitment of new staff with the expertise to develop the necessary research and development (R&D) programs and implement the nuclear waste management program.

It is worth noting that, at one point, the United States had progressed further than other countries and had submitted a license application in 2008 to the NRC for construction of a repository at Yucca Mountain. Since that time, both Finland and Sweden have submitted license applications for construction authorization. Finland's license was approved in 2015 and repository construction is underway (NWTRB 2016a). In Sweden, the license has been recommended for approval by the regulator and the Land and Environmental Court and is awaiting final approval from the Government (SKB 2021b). Following the current hiatus, the United States will eventually need to redefine a path forward, which could either be resumption of work on the Yucca Mountain Project or identification of a different site for a repository. It should be noted that if the Yucca Mountain Project proceeds, the current inventory of SNF already exceeds the statutory capacity limit of 70,000 MTHM for the Yucca Mountain repository, implying the need for additional repository capacity at Yucca Mountain or elsewhere to accommodate current and future generated SNF (Figure 1-6).

The lack of a defined path forward has limited the activities that DOE can undertake in support of moving towards an operating repository. DOE is currently carrying out two types of R&D activities. One type focuses on initiatives that are related to extended storage and transportation.

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[11] "Nuclear Waste Fund (NWF) Annual Financial Report Summary FY2019 and Cumulative." https://www.energy.gov/sites/prod/files/2019/12/f69/FY19%20-%20NWF%20Annual%20Financial%20Report%20Summary.pdf [Accessed on February 4, 2021].

The other type involves generic studies on geologic disposal of SNF and HLW, focusing on improving the understanding of repository behavior for different host rock types. This work implicitly acknowledges that developing a repository at a new site will take decades to reach the stage of accepting SNF and HLW for disposal (NWTRB 2015a). Even if the Yucca Mountain program were restarted, the time needed from resumption of the Yucca Mountain program to the start of operations would be around 13 years.[12]

Nevertheless, there are benefits from pursuing R&D to support the development of a repository and the necessary infrastructure in advance of a new plan being defined. These R&D activities could help reduce the timeframe needed to develop a repository after a policy decision is made. For example, the Board has identified technical infrastructure-related issues that can be addressed now, which will support development of a repository. These include moving forward with the development and approval of the DOE standardized canister (NWTRB 2017b) and retention and development of the needed workforce (NWTRB 2020).

3.2 Complex Structure of Responsibilities and Stakeholders

For a complex process such as nuclear waste management and disposal, progress is facilitated when the stakeholders align activities and work collectively toward achieving the goal. We observed that in those countries that are moving forward, such as Finland, Sweden, and Switzerland, generally the implementer (the entity responsible for transportation and disposal, as well as, in some cases, interim storage), Posiva, SKB, and Nagra, respectively, is the same as or has representation from the nuclear utilities. In these cases, the implementer, or its parent body, is involved in all aspects of the nuclear waste management program from generation to disposal. We also observed other characteristics of the programs in these countries that include high levels of public engagement in the process and a strong reliance on science and technology in making decisions about siting a repository.

France is also moving forward. In France, responsibility for transportation and disposal lies with the government through the national radioactive waste management agency Andra, the French implementer. However, the French government is also the majority owner of the fuel and reactor suppliers, the nuclear utility, and the SNF reprocessor, so it also has some level of responsibility for all parts of the nuclear waste management program.

The United States has taken a different approach, with nuclear power plants being operated by utility companies rather that the federal government. In 1982, Congress passed the NWPA, which assigned DOE the responsibility for transportation and disposal of the nation's commercial SNF and HLW, in addition to the responsibility it had for managing and disposing of the government's SNF and HLW. The NWPA also established the Office of Civilian Radioactive Waste Management within DOE. This has resulted in a partition of responsibilities across a wide array of government and industrial organizations, as depicted in Table 3-1 for commercial SNF. Table 3-1 indicates the entities associated with implementing each of the stages of the nuclear fuel cycle. The different colors indicate different organizations, and shades of a single color indicate entities acting within one organization (e.g., NRC). We consider that a

[12] NWTRB estimate based on information from GAO (2017) and DOE (2008, Figure 2-1).

Table 3-1. Matrix of Entities Associated with Implementation of Each of the Stages of the Nuclear Fuel Cycle Influencing the Back-End Stages.

Sector	Power Generation	Storage	Transportation	Disposal
Nuclear Industry	Fuel Vendor	Cask Vendor	Cask Vendor	No Direct Involvement
	Nuclear Utility	Nuclear Utility	SNF Title Owner[13]	
			Transporter	
NRC	Plant Licensing	Storage Licensing	Transportation Licensing	Repository Licensing
DOE	Fuel R&D	Storage R&D	Overall Responsibility including Transportation R&D	Overall Responsibility including Repository R&D

better, more effective process would be to energize the entities to operate collectively to make effective decisions for multiple stages of the fuel cycle shown in the columns.

With the responsibilities being fragmented in this way, the job of DOE to design, build, and operate a repository is especially complex because each entity is free to act in its own interests and focus on only its own area of responsibility, in some cases without needing to take account of how its decisions will impact other entities. Also, the legal framework may influence how an organization interacts with other organizations thereby constraining communications.

The fragmentation depicted in Table 3-1 presents many challenges to DOE in executing a nuclear waste management program. By way of example, consider the storage of commercial SNF (NRC 2016). Due to delays in establishing a repository and removing commercial SNF from nuclear power plant sites, nuclear utilities are transferring SNF from cooling water pools that are reaching capacity to on-site dry storage in canisters, resulting in the quantity of SNF in dry storage increasing over time (Figure 1-4). The nuclear utilities have determined that this mode of on-site storage is the most economical. Many factors related to these decisions, such as canister size and condition of the waste inside canisters, will ultimately impact transportation and disposal of the waste by DOE. The current trend, driven by nuclear utility economics, has been toward using larger canisters that can contain increasingly larger numbers of spent fuel assemblies, and thus have higher heat loads than the smaller canisters that were used earlier. If the SNF is directly disposed of in a repository in these larger canisters, i.e., without first repackaging the SNF into smaller canisters, challenges with respect to placement, heat load, and criticality issues could arise in repository design. If, however, the SNF is repackaged into smaller canisters prior to disposal, then substantial additional costs will be incurred, additional low-level waste volumes will be created, and there will be significant effort and additional dose risks for workers involved in the repackaging operations. This is just one example of how

[13] The SNF title owner has responsibility to arrange and provide for the preparation, packaging, inspection, and loading activities necessary for the transportation of SNF to the DOE facility.

decisions and actions by one entity in Table 3-1, in this case the nuclear utility, impacts the decisions and actions of DOE. The many colors (entities) in the implementation matrix in Table 3-1 emphasize the complexity of DOE's responsibilities.

In contrast to commercial SNF, better integration is possible for HLW and DOE-managed SNF, since DOE is responsible for all operations related to these materials. Nonetheless, we have observed cases where information and best practices could be much more effectively shared and integrated throughout the DOE complex, including between the various DOE offices, national laboratories, and contractors (NWTRB 2016b).

4 RECOMMENDATIONS

The lack of a national plan for the management and disposal of SNF and HLW and the institutional constraints outlined above have resulted in significant challenges for DOE. Despite this, we see significant opportunities for DOE to enhance its preparedness for creating a unified and integrated program on storage, transportation, and disposal by incorporating the broad, overarching recommendations presented in this report as core principles of such a program.

This Board notes that some countries are moving along the path to a geologic repository, with sites selected, licensing in progress, and, in the case of Finland, construction underway. It is instructive to examine these programs. Table 4-1 is an updated summary of the status of the repository development programs in 13 countries the Board surveyed for a report it issued in 2016 (NWTRB 2016a). In some cases, countries have had to reset their programs to complete site selection, most often due to public opposition (NWTRB 2015a). In other cases, countries still do not have a viable disposal program.

Much of the impetus for this report and its recommendation comes from what the current Board has learned from observing progress in waste management in other countries and at the Waste Isolation Pilot Plant (WIPP)[14] in the United States. Based on our observations while interacting with geologic repository programs in other countries, we have defined what we believe are a number of key attributes of programs in countries that appear to be on a successful path to building a repository (Box 4-1). These attributes directly influenced our six recommendations below.

Box 4-1. Characteristics of programs in countries on a path to building a repository

- A strong foundation in science and technology that benefits from independent external review
- Willingness to adapt and change in light of new knowledge and public input
- A major emphasis on transparency and openness
- A primary focus on demonstrating safety, building a safety culture, and instilling public confidence in both:
    - Short- and long-term safety through a clear articulation of the safety characteristics
    - Operational capabilities
- A consent-based process to select disposal sites (or at least a process that includes public engagement)
- Clear site-suitability criteria used to screen sites
- Long-term research programs (including international collaboration) in an underground research laboratory in rock similar to that at the proposed repository site

Working from our previous reports to DOE and from our interactions with programs in other countries, we have distilled six overarching recommendations that can be implemented now to help move forward in developing a nuclear waste management program in the United States to effectively address the nuclear waste issue and implement a geologic repository.

[14] The Waste Isolation Pilot Plant, located near Carlsbad, New Mexico, was constructed to dispose of defense-generated transuranic waste. The waste is permanently disposed of in rooms mined in an underground salt bed layer over 2,000 feet from the surface. Source: https://wipp.energy.gov/ [Accessed on February 5, 2021].

Table 4-1. Status of Repository Development in 13 Countries	
Country	**Status**
United States	A site at Yucca Mountain, in southern Nevada, was selected by Congress in 2002 (U.S. Congress 2002) and a license application was submitted in 2008.*
Belgium	The strategy for management and disposal was published in 2018 (ONDRAF 2018). No formal siting process has been initiated (ONDRAF 2020).
Canada	The "Adaptive Phased Management" plan, approved in 2007, is being implemented (NWMO 2020a) (see Box 4-3). Two areas are being studied, including site characterization at two sites.
China	The "Guidelines on Research and Development Planning for Geological Disposal of High-Level Radioactive Waste" was issued in 2006 (Wang et al. 2018). Site selection activities started in 1985 and site characterization efforts have been in progress since 2011.
Finland	The strategy for waste management and disposal was published in 2015 (STUK 2015). In 2015, the Finnish Government issued a license to construct a repository in Olkiluoto (STUK 2017). Excavation work for a disposal tunnel began in February 2021 and final disposal activities are expected to start in 2025 (Posiva 2021).
France	The "National Plan for Radioactive Materials and Waste Management" was published in 2017 (ASN 2017). Site characterization activities around the proposed Cigéo facility at Meuse/Haute-Marne are ongoing (Andra 2020).
Germany	A report summarizing the waste management strategy was published in 2015 (BMU 2015). In September 2020, 90 potential "sub-areas" in claystone, salt, and crystalline host rocks were identified in the site selection process (BGE 2020).
Japan	The site selection process was initiated in 2002 (NUMO 2020a). In 2020, two municipalities expressed interest to participate in the site selection process (NUMO 2020b, 2020c).
Republic of Korea	The "Basic Plan on High-level Radioactive Waste Management," published in 2016, defines the site selection process (IAEA 2017a). Site selection activities have been in progress since 2016.
Spain	The "6th General Radioactive Waste Plan" was approved in 2006 (MITYC 2006). The site selection process is planned to be initiated in 2023 (IAEA 2017b).
Sweden	The "Swedish National Plan" was published in 2015 (SSM 2015). A site at Forsmark was selected in 2009. The application for a license to construct the repository is currently under review (SKB 2021b).
Switzerland	The "Sectoral Plan for Deep Geological Repository" was published in 2008 (SFOE 2020). Three siting regions are being evaluated as potential repository sites and final selection is expected to be announced in 2022 (Nagra 2020).
United Kingdom	A report describing the waste management and disposal strategy was published in 2018 (BEIS 2018). Two communities have expressed interest to evaluate the potential of hosting a repository (Bailey 2020; RWM 2020a, 2020b).

*In 2010, the Administration determined that the proposed repository was "unworkable" and attempted to withdraw the license application that was pending before the NRC. The adjudicatory hearing, which must be completed before a licensing decision can be made, remains suspended and no work on the Yucca Mountain repository program is currently being undertaken.

These recommendations are discussed in the following subsections and are summarized in Figure 4-1. The first two recommendations deal with the design and effective operation of the nuclear waste management program under DOE. The next two recommendations provide guidance on creating a more effective and rigorous science and engineering program. The final two recommendations deal with building public trust and international engagement to foster success in the program.

We recognize that the nuclear waste management program needs better coordination and cooperation among all the various stakeholders in the implementation matrix (Table 3-1) and that DOE cannot force change outside of its purview. Likewise, full implementation of some of these recommendations, particularly those related to sustaining personnel and infrastructure, will require Congressional authorization and funding. But we suggest that changes within DOE based on the six recommendations will improve the effectiveness and efficiency of the nuclear waste management program, thereby accelerating progress toward the goal of implementing a geologic repository, and position the program to move forward effectively when decisions are made (even without legislative changes such as those that have been recommended by the BRC).

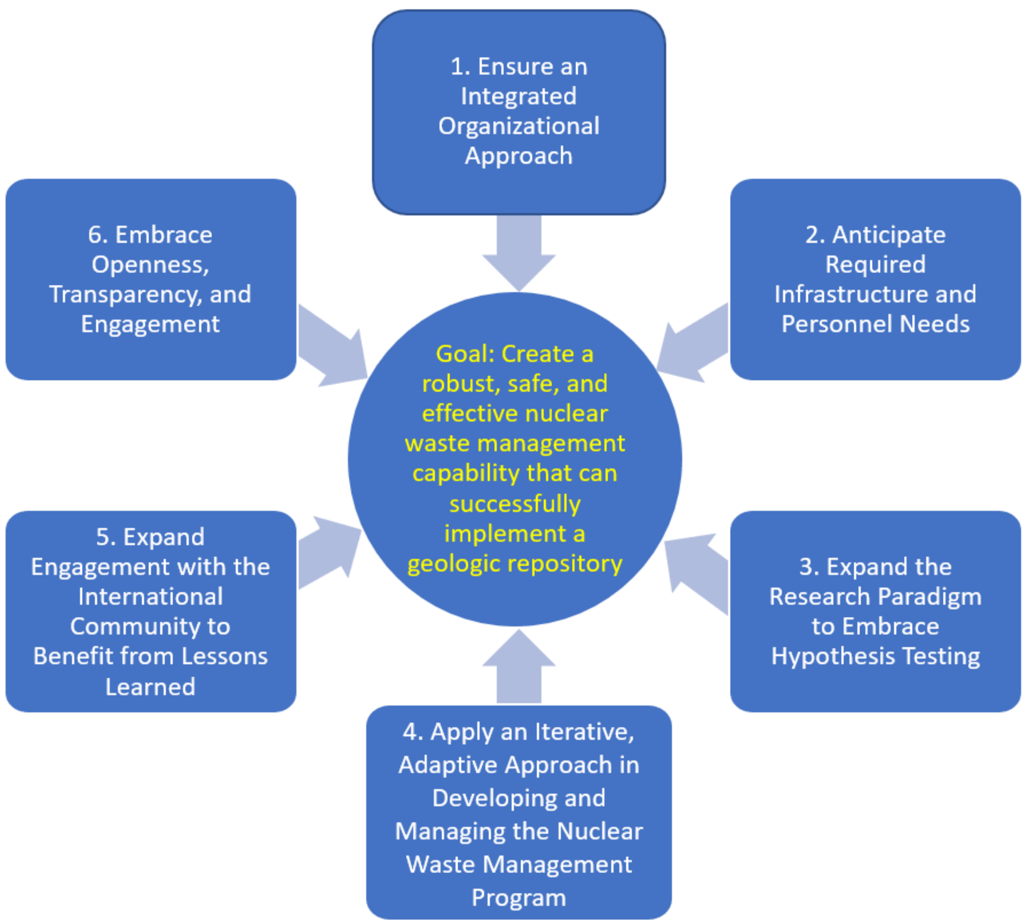


Figure 4-1. Six overarching recommendations for DOE's nuclear waste management program in support of developing a successful geologic repository program in the United States.

Finally, we recognize that DOE has made attempts in a number of its programs to address these issues. The six recommendations put forward here, if adopted as core principles, are intended to help DOE address issues that have proved challenging in implementing the nuclear waste management program.

4.1 Ensure an Integrated Organizational Approach

As discussed above, DOE faces challenges in developing an integrated nuclear waste management program given the number of entities in the implementation matrix in Table 3-1, the lack of a plan for developing a repository, and the lack of a federal mandate to integrate responsibilities and entities. However, we view integration as one of the most important factors that contribute to the development of a robust, effective, and safe waste management capability. For the past several years, Congress has provided funding to DOE for "integrated waste management system" activities, although the focus of the activities has changed over the years. The Board believes that this is a key component of the waste management challenge and should be vigorously pursued (NWTRB 2014, 2016b). As part of this section, some specific observations and recommendations are included.

This Board finds that there are several aspects of planning and coordinating an integrated waste management system that will require significant advance planning and early coordination with other stakeholders in the U.S. program. For example, designing, licensing, and acquiring a SNF/HLW transportation system require careful advance planning and sequencing of activities since the following tasks must be completed for full execution (NWTRB 2019a):

- Developing and licensing of new containers (casks and canisters) for DOE-managed SNF and HLW.
- Developing, licensing, and providing standardized canisters and a repackaging facility for commercial SNF, if they are needed.
- Resolving technical issues that may prevent the transport of commercial SNF casks and canisters that are not yet approved by the NRC for transportation.
- Ensuring that emergency planning and response programs are ready at the local and state levels, as well as across multi-state compacts and within tribal jurisdictions.

DOE has supported a number of publications that describe steps towards integration (DOE 2013, 2016; Jarrell 2016; Nuclear Technology 2017; Rechard et al. 2010), but we find that many aspects of the nuclear waste management program still lack the comprehensive integration required for implementing a successful repository program. The integration needs to take place both within DOE itself and between DOE and other agencies and entities as detailed below. Engagement with the public is an especially important aspect of integration that is singled out in a separate section, Section 4.6, rather than included in this section. We note that integration can take place at many levels such as integration of management and organizational integration. System management approaches can be utilized over a range of levels of integration. The observations and recommendations touch on all of these aspects.

Organizational integration is one of the most important factors in the development of a robust, effective, and safe nuclear waste management capability. Applying an integrated systems approach is particularly critical given the complexity of all the operations, processes, and subsystems involved. An integrated systems approach is needed to bring together the different subsystems so that they function together to provide the desired behavior of the system as a whole.

In addition to incorporating the sciences and technologies involved, integration of the different components of the waste management system (i.e., extended storage, transportation, and disposal) and the entities involved (i.e., governmental, commercial, and regulatory) is required to have a successful nuclear waste management program. In the Consolidated Appropriations Act, 2021 (Public Law 116-260; U.S. Congress 2020), Congress directed DOE to continue "integrated waste management system" activities. This is a key component of the waste management challenge and should be vigorously pursued. Calls for integration have been parts of numerous Board letters and reports and were also included in recommendations in the BRC report (BRC 2012). DOE has also recognized this need in its review of lessons learned during its own efforts (Rechard et al. 2010).

Better Program Integration Across the DOE Organization

A recurring theme in our letters and reports to DOE is the need for DOE to better integrate and share information across its offices, its national laboratories, and other contractors. The national laboratories share information effectively within some specific technical areas, such as the High-Burnup Dry Storage Cask R&D Project (EPRI 2014, 2020). In contrast, the Board and other entities (BRC 2012; National Academies of Sciences, Engineering, and Medicine 2019; National Research Council 2006) have found many instances where information sharing could be improved. As an example, even though there are considerable differences between the chemistry of the wastes that will be vitrified at Hanford and the wastes that have been vitrified at the Savannah River Site for over 25 years, the Board observed during its public meeting in 2013 that little information sharing had occurred between the two sites. The Board recommended closer collaboration among all DOE Office of Environmental Management (DOE-EM) sites involved in waste vitrification (NWTRB 2013a). The Board subsequently observed increased cooperation around topics related to glass corrosion in our more recent review of that topic in 2017 (NWTRB 2017d). The Board has been encouraged to hear researchers from different DOE laboratories express appreciation for the opportunity to see results from the work from other groups supported by DOE at poster sessions incorporated in Board public meetings. The Board is cognizant that the DOE Office of Spent Fuel and Waste Science and Technology holds annual working group meetings during which researchers on different projects can interact, but we believe that more such opportunities are needed for sharing and integration.

Another opportunity for improved integration is between the DOE Office of Nuclear Energy (DOE-NE) and DOE-EM. Improved integration would lead to greater efficiency and avoid difficulties in the development of a nationwide, integrated waste management system as indicated by the following examples:

- DOE-EM has developed and is using a transportation planning and coordination tool called Web-based Transportation Routing Analysis Geographic Information System

(WebTRAGIS) (Peterson 2018) for its waste. Subsequently and independently, DOE-NE developed its own transportation route-planning tool called the Stakeholder Tool for Assessing Radioactive Transportation (START) (DOE 2021). START has many of the same features as WebTRAGIS, and it is not clear why DOE-NE did not coordinate with DOE-EM to adapt WebTRAGIS to suit its needs.

- DOE-NE is developing several system analysis tools [Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS), Next Generation System Analysis Model (NGSAM), Multi-Objective Evaluation Framework (MOEF), etc.] to evaluate alternative approaches to designing and implementing a nuclear waste management system. However, after many years of development, the system analysis tools have been focused primarily on the management of commercial SNF, with only recent modifications to begin to deal with DOE-managed SNF and HLW.

- DOE-EM is planning to solidify the liquid sodium-bearing waste currently stored in underground tanks at INL, in preparation for the eventual transportation of the waste away from the site and its disposal. It is not yet clear whether this waste will need to be classified as HLW, which will require disposal in a HLW repository, or if it can be classified as transuranic waste, in which case it will be able to be disposed of in the WIPP facility. However, DOE-EM has already made the decision to process the waste on the assumption that it will be classified as transuranic waste, and procured canisters that are compatible with the equipment used to transport waste to, and disposal of waste at, WIPP. The canisters being used, and those being developed, for packaging of HLW all have smaller diameters than the canisters procured for packaging the sodium-bearing waste at INL. Consequently, if the sodium-bearing waste is ultimately classified as HLW, handling the sodium-bearing waste packages at a HLW repository may encounter compatibility problems because of the larger diameter of the canisters. This appears to be an example of both poor integration and lack of information sharing between DOE-EM, which is responsible for processing the sodium-bearing waste, and DOE-NE, which is responsible for developing the nuclear waste management program, including the repository for SNF and HLW (NWTRB 2016b).

There are also opportunities to share information and collaborate with other offices within DOE and other government agencies. For example, the CO_2 underground storage research program in DOE's Office of Science is working to characterize physical and chemical processes acting in the subsurface, which are R&D topics relevant to geologic disposal.

The Board recommends the following actions for DOE management to improve integration across the DOE program for SNF and HLW management and geologic disposal:

- **Foster broader sharing of information among DOE offices, national laboratories, and contractors (e.g., university researchers supported by Nuclear Energy University Program grants).**

- **Further enhance integration of R&D programs executed by DOE-EM, DOE-NE, and other DOE offices to optimize collaboration, minimize duplication, and maximize the effectiveness of the effort.**

Better Communication and Engagement with the Nuclear Industry

As indicated earlier, the fragmentation and distribution of responsibilities across the private and public sectors shown in Table 3-1 adds to the challenges associated with the placement of commercial SNF in a repository. In addition, an already noted challenge is the impact of larger and hotter dry-storage canisters for commercial SNF. In addition to changes in storage canisters, new cladding and fuel materials and higher enrichments are all being considered for deployment, in this case with partial DOE support. Even though DOE participates in these activities, the Board has not seen any assessment by DOE of the impact of the new fuels on disposal packaging requirements and repository performance. A 2019 workshop involving DOE, NRC, Electric Power Research Institute (EPRI), and industry on the implications of advanced fuels on extended storage and transportation was a positive step in this direction.[15] Had this taken place earlier, DOE could have assessed the impact of advanced fuels on the back-end stages and provided more timely input to the ongoing R&D.

The Board recommends the following specific actions for DOE management to improve integration with the nuclear industry:

- **Find ways to work with utilities, cask vendors, fuel manufacturers, and others in the nuclear industry in an ongoing manner, to more effectively develop and implement the nuclear waste management program.**

- **Find additional innovative ways of information sharing through DOE-led conferences or workshops that might encourage the different entities in the implementation matrix in Table 3-1 to improve communications and engagement.**

4.2 Anticipate Required Infrastructure and Personnel Needs

Solving a problem as complex as nuclear waste management depends upon having an adequate physical infrastructure that includes facilities, equipment, and information technology, as well as the requisite human resources to provide technical, management, and public outreach capacity. Furthermore, the length of time it takes to design and develop a repository requires a long-term plan for maintaining such infrastructure and educating personnel into the future. Developing the needed infrastructure for the U.S. nuclear waste management program has required decades and will continue into the future. The needs in terms of physical and human capital must similarly be explicitly addressed for the long term, and continually re-evaluated.

[15] EPRI Extended Storage Collaboration Program Workshop on Evaluating Advanced Fuels Impacts (Accident Tolerant Fuels and Higher Burnup/Enrichment) on Back-end Operations held November 4, 2019 in Charlotte, North Carolina.

After nearly a decade of reviewing DOE activities, the current Board has identified in many of its previous reports[16] opportunities for DOE to sustain and improve critical infrastructure. However, we are not aware of any recent integrated assessment by DOE to identify the near-term critical infrastructure necessary to carry out its R&D mission and support the nuclear waste management program. Such integrated planning should be a sustained, ongoing effort. A well-developed and understandable plan is a key asset in communicating the needs to those who make funding decisions.

The need for integrated planning for these key functions is heightened by the fact that the work on the nuclear waste management program is distributed among a number of national laboratories, each with its own management structure and technical capabilities. With storage facilities for DOE-managed SNF operating for much longer than originally anticipated, the Board has observed that DOE has developed aging management plans for some, but not all, of these facilities (NWTRB 2017b). In addition, not all of the already developed aging management plans have been implemented and these should move forward.

Along with managing aging facilities, DOE needs to maintain and enhance capabilities for computational simulation. Overall, DOE is a world leader in the development of leading-edge, high-performance computing systems and associated application software. The available computing infrastructure and software enable simulation of complex systems and processes. The nuclear waste management program has to date taken some advantage of these capabilities in modeling the back-end-of-the-fuel-cycle processes and systems. Ongoing development of models and solution algorithms will be required to fully utilize the capabilities of evolving leadership-class, high-performance computing systems, e.g., Exascale computer systems.

Furthermore, given the very long timescale for developing, implementing, and monitoring a nuclear waste management program to dispose of SNF and HLW, there is a critical need for an integrated data management infrastructure to preserve and easily access data, including metadata and experimental samples. The Board acknowledges that DOE has done this for SNF and is in the process of doing this for Yucca Mountain-related material (NWTRB 2013b).

The long and tortuous path of developing a geologic repository in this country has also taken its toll on the workforce capacity. Persons with critical expertise have left the workforce, particularly since the hiatus with the Yucca Mountain Project, resulting in a potential future gap in critical expertise. The Board commends the Sandia National Laboratories for implementing a strategy for knowledge management for the Nuclear Energy Fuel Cycle Sub-Program (Bonano et al. 2019). This strategy was developed to address the loss of institutional knowledge when experienced staff members, who were seasoned subject matter experts and mentors, left the workforce and there was an influx of new staff. DOE plans to establish a knowledge management program, initially focused on disposal research R&D, but eventually expanding to all back-end-of-the-fuel-cycle activities (Sassani et al. 2020). DOE is currently engaged in several activities, such as conducting knowledge management workshops and meetings and developing a pilot knowledge management information system. Regarding future hires, this Board believes universities are not necessarily producing graduates in subjects relevant to the nuclear waste management program. Specifically, a potential dearth of trained experts in

[16] Board reports are available at https://www.nwtrb.gov/our-work/reports [Accessed on March 23, 2021].

subjects related to geologic repositories is to be expected in the next years and decades if no action is taken.

Based on these observations, the Board recommends the following specific actions for DOE to address infrastructure and personnel needs:

- **Develop and communicate an integrated plan regarding physical infrastructure, information technology, and personnel needs over the next decade.**

- **Formulate and implement research programs and other supporting infrastructure consistently to anticipate the effects of aging of facilities.**

- **Develop and maintain the capability to utilize DOE's leading-edge, high-performance computing resources for the analysis and simulation of processes and systems related to the back-end of the fuel cycle.**

- **Develop infrastructure for and implement data management systems that can meet the needs for long-term, open, and efficient retrieval of information from current and, to the extent possible, previous relevant R&D programs.**

- **Address the challenges of an aging workforce by expanding mentorship of a new generation of staff through: technical training programs; more effectively targeting undergraduate scholarships, graduate fellowships, and post-doctoral fellowships in areas of need; establishing internships at URLs; and promoting careers in nuclear waste management as an opportunity to address this grand environmental challenge.**

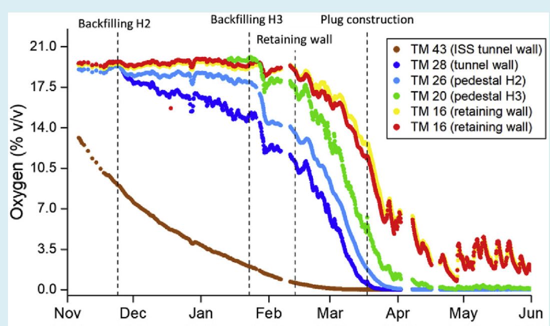
4.3 Expand the Research Paradigm to Embrace Hypothesis Testing

Presentations made to the Board on DOE research programs addressing technical issues related to dry storage, transportation, and disposal often include comparisons of model calculated results with experimental or field data. In some cases, the purpose of the comparison is model validation, i.e., to address the question of whether the model is able to adequately represent the data. In other cases, the data are used to calibrate model parameters in order to improve model effectiveness. This dual purpose of comparing model results with observations for both model validation and calibration, needs to be done with care to avoid model over-fitting and allow generality, i.e., good performance in situations that the model has not seen before. For example, lack of investigating why initial model results differ from experimental or field results can preclude identification of new processes or properties that were not incorporated into the original underlying conceptual model. In other words, reliance on parameter calibration may implicitly allow a model to yield successful predictions in a specific situation, but not in others where an unknown phenomenon is manifested. It is not uncommon, for example, that multiple parameters in the model can be adjusted within physically reasonable limits to match observations (the phenomenon of equifinality). Calibration thus can hide unidentified processes and emergent behavior that could be important for the evolution of a repository environment under natural or perturbed conditions. In fact, principled model validation across a wide range of scenarios is needed to identify critical model parameters, processes, and conditions under which models may fail to yield reliable predictions.

A good example of this was described by Giroud et al. (2018) for work toward a proposed SNF and HLW repository in Switzerland, which is highlighted in Box 4-2. This example emphasizes

Box 4-2. Example of hypothesis testing at the Mont Terri underground research laboratory in Switzerland

Waste emplacement and other repository operations allow oxygen into underground areas of a repository. After the repository is sealed, oxygen continues to react with the rock and its pore fluids, waste canisters, and other emplaced materials. Once the oxygen is consumed, reactions of the water in the repository with the emplaced metals are expected to generate hydrogen, creating what is referred to as electrochemically reducing conditions, the desired state for the repository. Investigating the length of time the repository remains aerobic (oxygenated) is important both in terms of understanding the onset of hydrogen generation and in terms of limiting the length of time that pitting, a type of problematic, oxygen-driven corrosion, of canisters can occur. Within the Swiss repository program, it was generally thought there would be a period of a few years to several decades after emplacement of the waste during which oxygen would be available in the repository. This time range was based on models that simulated multiple processes of oxygen consumption. As part of the Full-scale Emplacement (FE) experiment at the Mont Terri underground research laboratory (Figure 4-2a), Giroud et al. (2018) investigated oxygen consumption in the bentonite backfill of the experimental drift at Mont Terri. The experiment showed that oxygen was consumed within weeks to months (Figure 4-2b), disappearing in the deepest parts of the experiment even before it was sealed. Instead of re-calibrating older models to reflect this observed rate, emphasizing reactions with canister metals or rocks, the researchers designed benchtop experiments to investigate new hypotheses related to the materials used in the field experiment. They used information from the FE and the benchtop experiments to pin down the likely mechanism controlling the oxygen, and then incorporated this process — oxygen sorption on bentonite backfill — into a new model.



(a) (b)

Figure 4-2. Full-scale Emplacement experiment. (a) Board delegation learns about the experiment. (b) Oxygen concentration in the bentonite backfill pore space during and after backfilling and sealing of the Full-scale Emplacement experiment (Giroud et al. 2018). (Note: % v/v — percent by volume).

that model development should be a continually evolving process where conceptual models are updated as new knowledge is developed and more data become available. DOE should further embrace a healthy "scientific skepticism" when these models are used for hypothesis testing: a model that is calibrated and validated against today's data may not be similarly acceptable in the face of newly collected data, such as the field and benchtop data for oxygen described in Box 4-2, opening opportunities for model improvement. The DOE R&D plans for storage and transportation (Saltzstein et al. 2020) and for disposal (Sassani et al. 2020) acknowledge the need to be flexible to account for changes in research priorities and funding and, yet, such flexibility has not always been manifested in day-to-day endeavors.

As demonstrated in the example of oxygen consumption, the ultimate test of laboratory and computer modeling studies is research carried out under the physical, chemical, and hydrologic conditions of a future repository. Such conditions are most adequately simulated in a URL. As highlighted earlier in Box 4-1, URLs are considered a key component of the repository programs of nearly every country with active repository development programs (e.g., France, Sweden, and Switzerland) (NWTRB 2020). These countries utilize URLs for a wide range of scientific experiments, testing operational capabilities, and, in many cases, in support of public outreach. In fact, the Aspö URL in Sweden, located in the same rock type and at the same depth as the planned repository, is in the top 20 of Sweden's tourist attractions (NWTRB 2019b). A dedicated URL, separate from a proposed repository site, has not been a component of the U.S. repository program, although the United States has been an active participant in scientific experiments in a number of URLs in other countries.

Conducting research in URLs leads to a more complete scientific understanding of coupled processes and improved capability for predictive models (NWTRB 2020). URLs enable detailed characterization of the undisturbed rock and the hydrogeologic, mechanical, geochemical, and microbial environment at depth, as well as characterization of the in-situ behavior of engineered barrier system components. Experiments can be conducted to assess the impact and interactions of waste heat and disposal system components on the subsurface geologic environment at spatial and temporal scales that are relevant to repository conditions. For example, while typically only single fractures in rock can be studied in standard laboratory tests, entire fracture systems can be probed in URLs.

To date, all repository programs have encountered surprises and unanticipated challenges and, as demonstrated by the oxygen consumption example, URLs have sometimes revealed these surprises. In the example of the one-to-one scale FE experiment completed in a URL, oxygen consumption was so rapid that it was too late to obtain meaningful data in parts of the drift for the rate of change of oxygen concentration (NWTRB 2019c; Giroud et al. 2018). The oxygen consumption example is also elucidating in that the research team concluded that sorption of oxygen on bentonite is likely the fastest oxygen-consuming process, but the influence of microbial activity on oxygen availability was another possibility (Giroud et al. 2018). Sweden's research focus on the impact of microbial activity within a repository was at least partly generated from some early serendipitous studies by a curious young researcher (NWTRB 2020). At least partly as a consequence, Sweden participated in the Microbiology in Nuclear Waste

Disposal (MIND) program,[17] which investigated biotic processes and their effect on safety and performance of future repositories.

URLs also enable in-situ monitoring of physical and chemical parameters within large rock volumes using new sensor technologies. For example, work in the Meuse/Haute-Marne URL in France has allowed exploration of the feasibility of constructing large galleries, a problem that had not been considered at the outset (NWTRB 2020). Such monitoring can result in the generation of large experimental data sets, requiring processing that utilizes leading-edge, high-performance computing facilities, with the potential of yielding improved understanding and modeling capability.

Drawing upon our reviews of research approaches in other countries and our observations of the DOE program, we recommend the following actions for DOE to expand its research strategy:

- **Anticipate surprises or unexpected results that may arise during the R&D program and assure all research programs include ample provisions to accommodate possible changes in direction and focus.**

- **Test alternative hypotheses using careful experimental design over multiple scales from laboratory to full-scale in-situ tests in a URL.**

- **Continue to make new measurements to build a database that tests the abilities of existing models to capture important processes and evaluate the possible need for new conceptual models to improve estimates of system properties and thus prediction accuracy.**

- **Use results of repeated testing of existing and evolving hypotheses to enhance the usefulness of models in performance assessment.**

- **Establish one or more dedicated domestic URLs that will provide the necessary opportunities for researchers and students to conduct in-situ investigations into subsurface processes at scale, test models, and further international collaboration.**

4.4 Apply an Iterative, Adaptive Approach in Developing and Managing the Nuclear Waste Management Program

Implementing an iterative, adaptive approach for managing and disposing of nuclear waste has been recommended by international organizations (e.g., NEA 2004a, NWMO 2005) and the BRC (2012), and has often been embraced by DOE (e.g., Rechard et al. 2010). A National Research Council (2003a) report argued that:

> *"Compared to other large engineering projects, geologic repositories for high-level waste present distinct challenges because: (i) they are first-of-a-kind, complex, and long-*

[17] The MIND program was an international multidisciplinary project funded by the European Commission from 2014 to 2018. See https://www.mind15.eu/about/ [Accessed on March 23, 2021].

term projects that must actively manage hazardous materials for many decades; (ii) they are expected to hold these hazardous materials passively safe for many millennia after repository closure; and (iii) they are widely perceived to pose serious risks."

The report concluded that an adaptive approach is needed for the entire waste management system. Such an approach is, by definition, iterative. It emphasizes continuous learning, both technical and societal, and includes regular scientific and managerial re-evaluations and reactions to new knowledge, is responsive to stakeholder input, and is designed to continually improve the project while retaining the option of reversibility or change.

These core principles are equally applicable today, and are equally applicable whether DOE completes a repository at Yucca Mountain or is directed by legislation to develop a repository at a new site. An iterative and adaptive approach — called adaptive staging in the National Research Council (2003a) report — will be necessary in either case, leading this Board to endorse the following recommendations outlined in that report to address these challenges:

- *"DOE should adopt Adaptive Staging."*
- Without compromising their independent roles, DOE and the NRC should work together to ensure that the regulatory process enables the application of Adaptive Staging in licensing a repository.
- *"DOE should consider the impact of Adaptive Staging on the overall waste management system."*

In endorsing the last bullet, we recognize that the need for an iterative, adaptive approach applies to DOE's overall program management as well as to its research activities related to the nuclear waste management program.

The iterative, adaptive approach to nuclear waste management and disposal is exemplified by the Adaptive Phased Management (APM) plan adopted by the Nuclear Waste Management Organization (NWMO), the implementing organization for Canada's nuclear waste program. The APM, which is described in Box 4-3, involves both transportation and disposal aspects of nuclear waste management. According to NWMO (2021a), APM

"…involves realistic, manageable phases, each marked by explicit decision points. It allows for flexibility in the pace and manner of implementation, and fosters the sustained engagement of people and communities throughout its implementation."

A fundamental tenet of APM is incorporation of new knowledge, including advances in technical knowledge, international best practices, ongoing public input, public policy changes, and evolving societal expectations and values (NWMO 2021a). The plan for implementing APM was developed taking account of input from the public and stakeholders.

Other examples of adaptive management of large-scale R&D programs addressing complex environmental problems, including non-nuclear-waste-related ones, such as restoration of the Everglades ecosystem in South Florida (USACE and SFWMD 1999; National Research Council

Box 4-3. Canada's Adaptive Phased Management plan

Adaptive Phased Management (APM) is Canada's plan for the long-term management of spent nuclear fuel. The plan, which is being implemented by the Nuclear Waste Management Organization (NWMO), involves the containment and isolation of spent nuclear fuel in a deep geologic repository. APM involves both a technical method and a management system (NWMO 2020b).

The technical attributes of APM are:

- Centralized containment and isolation of spent nuclear fuel in a deep geological repository
- Continuous monitoring
- Potential for retrievability
- Optional temporary, shallow underground storage prior to emplacement (not currently in NWMO's implementation plan)

The management system attributes of APM are:

- Flexibility in pace and manner of implementation
- Phased and adaptive decision-making
- Responsive to advances in technology, research, Aboriginal Traditional Knowledge, and societal values
- Open, inclusive, and fair siting process to seek an informed and willing host community
- Sustained engagement of people and communities throughout implementation

APM is designed to be implemented in six phases (NWMO 2021b): (i) site selection and regulatory approval, (ii) site preparation and construction, (iii) operations, (iv) extended monitoring, (v) decommissioning and closure, and (vi) postclosure monitoring. NWMO initiated the site selection process in May 2010. Site selection and regulatory approval are expected to take many years to complete, followed by an estimated 10-year period to construct the repository facilities.

2003b) and impacts of dam releases on a broad range of resources in the Grand Canyon (National Research Council 1999), strongly emphasize the need for input from external reviews. Indeed, many of the Board's public meetings reviewing DOE R&D activities have included participation by scientific experts involved in the geologic disposal programs in other countries, and DOE participants have expressed appreciation for the opportunity for discussion with these outside experts. Likewise, in the workshop run by the Board on the potential disposal of SNF and HLW in deep boreholes, DOE participants were laudatory of the opportunity this workshop provided them for intense and focused discussion with outside experts drawn from academia and the petroleum industry both inside the United States and from other countries (NWTRB 2015b).

In Sweden, the implementer's R&D program is reviewed triennially by both the regulator, who solicits input from public, and the Swedish National Council for Nuclear Waste, the Swedish counterpart to the Board. One of the benefits of external reviews is that such reviews can raise scientific or technical issues not considered within the program. As noted in Section 4.3, a serendipitous study by a young researcher in Sweden resulted in SKB initiating a significant research focus on the impact of microbial activity within the repository (NWTRB 2020).

Based on the Board's experience in reviewing DOE programs, we also believe that DOE should undertake the following actions, all of which will require an iterative, adaptive approach for successful implementation:

- **Iterate between testing individual components of the nuclear waste management program and testing integrated models of the entire waste management system, always being ready to adapt each approach based on what is learned from such testing.**

- **Be open and structured to adapt to surprises during all aspects of the nuclear waste management program and always be willing to reevaluate and rethink previous decisions.**

- **Establish mechanisms as part of on-going evaluations to facilitate and incentivize solicitation of input and feedback from all affected stakeholders, including: independent scientists and engineers outside of the nuclear waste management program; local, state, and tribal governments; nuclear utilities; and the interested public.**

4.5 Expand Engagement with the International Community to Benefit from Lessons Learned

The United States is not alone in conducting the R&D in support of the permanent disposal of SNF and HLW in a safe manner, and DOE and the national laboratories have long been involved in a number of international programs (see Section 4.3). The international community has vast experience in program integration, siting, iterative adaptive staging, research strategy, operational readiness, transparency, public dialogue, and engagement of stakeholders. This international experience led us to track developments in waste management and disposal programs in other countries. Through engagement with researchers and counterpart agencies in other countries, as well as visits to a number of facilities in other countries, we learned of a variety of initiatives in these countries facing challenges similar to those in the United States. Regardless of whether or not the United States decides to implement the Yucca Mountain option or embark on a new geologic disposal siting program, much can be learned from this international experience (see Box 4-1).

We can cite many important lessons learned from the international community. One important lesson is the value and necessity of public engagement from the outset. Other countries have also demonstrated that a geologic repository program must be built upon recognition that it takes decades to characterize the subsurface so as to enable and test effective models of the waste package–engineered barrier–rock system. The modeling is in itself a multi-decade effort.

Another lesson from international experience relates to research strategy. Many of the programs in other countries have compared and assessed some of the sub-models used in repository performance assessments. For example, the INTRACOIN, HYDROCOIN, and INTRAVAL projects initiated in the 1980s compared computer codes for groundwater flow and radionuclide transport (Larsson 1992). The DECOVALEX project compares models of coupled thermo-hydro-mechanical-chemical processes in geologic systems, in preparation for the ultimate goal of scaling up or integration into models of repository performance assessment. DOE has been and continues to be actively engaged in the DECOVALEX project (Birkholzer 2019).

While some might argue that international information sharing is superfluous because other countries are targeting host rocks that are different than those being targeted in the U.S. program, many scientific and technological issues are common among different host rocks and environments. International collaborations have been instrumental in data collection and in testing and comparison of models and in revising them to better represent the important physical processes, regardless of the target rock or repository environment.

The Board commends DOE for its increasing international collaboration in the nuclear waste management area (Birkholzer 2019). Participation in the "Clay Club" and "Salt Club", and interactions with the International Atomic Energy Agency (IAEA) and Organization for Economic Co-operation and Development Nuclear Energy Agency have enabled DOE to gain insights from best practices, innovative approaches, and notable successes and failures that have emerged from the experiences of the various international programs. DOE has gained similar benefits for issues related to storage and transportation by its participation in the EPRI Extended Storage Collaboration Program and the IAEA Spent Fuel Management network. Early engagement with its counterparts in other countries, while they are developing and implementing their programs, will let DOE benefit from the lessons-learned during these stages of the efforts made by those organizations. Although such engagement will require some expenditures, the net result might ultimately be cost-saving.

To better integrate lessons learned from the international community, we recommend that DOE take the following specific actions:

- **Build on current initiatives and continue to expand engagement with the international community, recognizing the need for global cooperation in science and technology in this world-wide grand environmental challenge.**

- **Sustain active engagement in international programs given the tangible benefits derived from close involvement.**

- **Continue and expand participation in collaborative international URL activities. If, as recommended in Section 4.3, DOE develops one or more URLs, it should encourage international participation, which could benefit the DOE program by incorporating broader perspectives and expertise.**

- **Emphasize engagement with countries that have advanced to the demonstration and/or construction authorization stages of repository development to enhance knowledge of these stages.**

4.6 Embrace Openness, Transparency, and Engagement

In licensing a repository in the United States, as well as in other countries, the goal is to show that the safety requirements in applicable standards and regulations are met. In the United States, the process primarily involves providing technical information for review by NRC technical experts. The goal is reached in multiple stages, initially when DOE obtains a construction authorization from NRC, then later when DOE obtains a license to receive and possess SNF and HLW, and subsequently when DOE obtains approval to permanently close the repository.

Experience in the United States and in other countries has demonstrated that geologic disposal of waste is as much a social challenge as a technical challenge (NWTRB 2015a, Stanford University and George Washington University 2018). The technical and social challenges may be addressed simultaneously or sequentially to enable licensing and construction of a repository (NWTRB 2015a), and may require some review and design modification as surprises emerge. Figure 4-3 illustrates these ideas by emphasizing the importance of both the technical and social "filters". If a siting program is to move forward, the site must meet the criteria specified by the two filters (i.e., the overlapping zone in Figure 4-3). The figure also illustrates that site selection is likely to be iterative and adaptive (see Section 4.3).

Most countries, including the United States, initially only focused on the technical issues in their programs only to belatedly discover that the attainment of social acceptability was every bit as important and difficult to navigate as the attainment of technical suitability. Over the last half-century, at least 24 efforts to site a deep-mined, geologic repository were carried out by implementers of national waste management programs in more than a dozen countries. In five of these efforts a site was chosen, whereas nearly one-half of the initiatives ended prematurely because the projects failed in the arena of social acceptability (Stanford University and George Washington University 2018).

As an example of how technical suitability intersects with social acceptability, consider the selection of site-suitability criteria. These criteria are initially of a generic nature (e.g., lack of seismic activity) with respect to identification of candidate sites. Having identified candidate sites, criteria that are more site specific (e.g., host-rock dependent) are developed to further screen these sites. Given that the site-suitability evaluation will contain technical content,

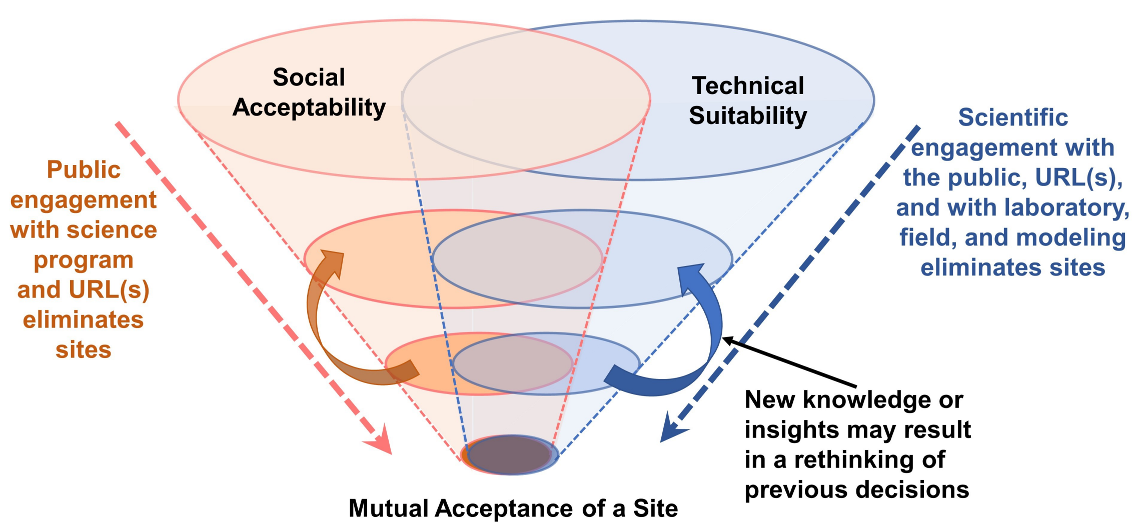


Figure 4-3. Development of a convergent pathway for siting a geologic repository. Based on NWTRB (2015a).

gaining public trust in this evaluation is important to gaining social acceptability. For example, by minimizing ambiguity in site-suitability criteria, latitude in interpretation can also be minimized, thereby helping enhance social acceptability (NWTRB 2015a).

We have sought to understand the key elements behind programs where forward movement in site selection has been successful. In France, Sweden, and Switzerland, we observed two key elements. First, their programs developed for the public a concise, easy-to-understand articulation of the safety characteristics of the repository based on sound science and proven technology. Second, the countries each developed one or more URLs to probe the subsurface environment and test operational aspects of the program, while familiarizing the public with the findings and decisions underlying the facility's safety.

Both of these elements emphasize the need for transparency and openness with the public during the entire trajectory of development of the geologic repository. Indeed, the tenets of openness, transparency, and engagement are well founded in the social science theory of solving large, technical, and socially-relevant challenges (Fischer 2000). These tenets have featured prominently in reports to DOE about waste management as far back as the early 2000s. For example, the National Research Council (2003c) report assessing DOE's long-term stewardship of wastes stated as a specific recommendation:

> *"Involve the stakeholders from the earliest phases of decisions that involve risk management. DOE should foster a positive working relationship with interested parties to work together to achieve common goals of protecting human health and the environment."*

In another report (National Research Council 2003a), the authors stated that:

> *"Transparency creates the basis for a dialogue among the implementer, the regulator, external review bodies, and stakeholders."*

A clear articulation of safety is essential for this dialog (Box 4-4). It is important to note that public engagement does not guarantee success of a program, but the lack of public engagement appears to greatly increase the probability for failure of such a program (NWTRB 2015a).

In some countries, the repository programs were driven to openness, transparency, and stakeholder engagement by laws that govern the disposal program. In other instances, they

Box 4-4. Necessary attributes for effective articulation of safety in a repository program

In the National Research Council (2003a) report "One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste," an argument was advanced that the articulation of the safety of a repository program:

1. must be understandable to non-experts
2. must describe the assumptions and concepts that underlie the performance assessment
3. must discuss the uncertainties that could result from limitations in the scientific understanding
4. must use other non-quantitative arguments (such as comparisons with independent lines of evidence, including historical or natural analogs among others) to support the plausibility of the safety-relevant behavior of the repository system.

discovered the need for well-conceived public engagement strategies along the way. For example, as stated in Section 4.4, Swedish law requires a triennial review of the implementer's R&D program by the regulator that includes input from the public. Sweden has adopted transparency, openness, and engagement with stakeholders as a fundamental tenet of its program (NEA 2004b). Disposal programs in other countries, such as Canada, Japan, and United Kingdom, have adopted a similar approach (NWMO 2020c, NUMO 2020d, Bailey 2020). In France, public debate at several stages of the disposal program is required by French law, which encourages the development of a description of the safety characteristics early in the disposal program that then become the focus for research, development, and demonstration for public involvement. The importance of incorporating the attributes of transparency, openness, and engagement with stakeholders has been consistently communicated to the Board by those in senior leadership positions from countries that are on paths to a successfully developed nuclear waste management capability (Gaus 2020).

In contrast, the U.S. law only requires a description of how the repository meets safety requirements at the time a license application is submitted.[18] However, this does not preclude DOE from engaging with the public during the development of the nuclear waste management program. While in certain instances DOE has funded non-governmental organizations and citizens advisory boards, public engagement often occurs late in the process, and after key decisions have been made. Moreover, it may involve an adjudicatory process. When public opposition has created delays in nuclear waste disposal programs in the United States and other countries, such public opposition can often be traced, at least in part, to lack of early engagement of affected stakeholders, including the public, in planning and review (NWTRB 2015a). A recent example of a U.S. program that did not move forward, at least partly attributable to a lack of transparency and early engagement with the public, was DOE's unsuccessful attempt to secure approval to drill a test borehole in North Dakota, in support of developing deep borehole technology as an option for disposal of SNF and HLW (Voosen 2016).

Finally, for engagement with the public to be successful, it must go well beyond providing information and dialogue. The Board has observed that countries in which the public was assured that decisions were based on good science and proven technology (Finland, France, Sweden, and Switzerland) are well down the path to successfully moving forward (NWTRB 2013c, NWTRB 2016a). These countries included stakeholders as informed, empowered principals in their process (NWTRB 2015a). When the public has the ability to have major impact on the program, this can influence the scientific agenda. For example, the program in France did not originally plan for reversibility until the public insisted on it (Landais 2018). This demonstrates that for a nuclear waste management program to succeed, some technical problems that must be solved may in part be defined ultimately by the public, and not solely by scientists and engineers. Acknowledging and planning for this requires engagement, openness, and transparency throughout the program from initiation through operation. We note that programs (e.g., in Sweden and Finland) that have been successful in moving forward have made public

[18] Moreover, Title I of NWPA, "Disposal and Storage of High-Level Radioactive Waste, Spent Nuclear Fuel, and Low-Level Radioactive Waste State and Affected Indian Tribe Participation in Development of Proposed Repositories for Defense Waste," focuses almost exclusively on site characterization rather than developing the repository concept and meeting safety requirements as other countries do.

engagement and building public and stakeholder trust vital components of their disposal programs.

The Board recommends that DOE implement the following specific actions in the nuclear waste management program, acknowledging that some of these actions only apply if the site selection process is reinitiated:

- **Inform and engage the public and other affected stakeholders early in the planning and review of all aspects of the nuclear waste management program.**

- **Be transparent in decision-making and provide support for meaningful stakeholder participation.**

- **Take account of lessons learned in other countries about listening to and informing the public, in order to improve communications, better understand community perspectives, and avoid unnecessary delays of the program.**

- **Though not a license requirement for any new site selected for a repository, DOE should develop and make available a clear characterization of the facility early in the process that describes the waste management concept and its multiple barriers and other attributes that contribute to safety. DOE must also clearly acknowledge and communicate its commitment that the safety concept will be revised to update it as new information and input are received.**

- **Develop site-suitability criteria prior to the start of site selection so as to minimize any ambiguity and latitude in their interpretation, thus helping to ensure the objectivity of the process and public confidence in its outcome. If, at any point during the siting process, the criteria need to be changed, a transparent and meaningfully participatory process to do so needs to be followed.**

- **If, as recommended in Section 4.3, the United States develops one or more URLs, these laboratories, in addition to their research function, should be utilized for outreach and public engagement, in order to provide access to the subsurface (a vague concept with the public) and to build public confidence and trust in the science and engineering behind the safety concept as well as in the operational capabilities for remote handling of waste underground.**

5 CONCLUDING COMMENTS

In this report, we emphasize six high-level, overarching recommendations that DOE should implement as core principles as it moves forward in its goal of developing a robust, safe, and effective nuclear waste management program for the nation, including laying the groundwork for a successfully implemented geologic repository. We recognize that the constraints discussed throughout this report, and especially in Section 3, make the implementation of some aspects of the recommendations challenging, at least in the near term. We also recognize that to implement the recommendations made here will require important contributions from entities in the implementation matrix in Table 3-1 that are beyond DOE's control. Nonetheless, we believe that adopting these recommendations as core principles will allow DOE to move forward in some areas even now and we have highlighted specific sets of actions that could be implemented to contribute to ongoing forward movement within the program. The tasks that can be implemented by DOE in the near term could be continued by a new implementer if established by policy makers. We suggest that these recommendations be considered core principles because it is clear that they will require long-term sustained commitment and effort.

In some instances, our recommendations (Figure 4-1) imply an expansion of current approaches, and in other cases they involve new ways of doing business by all the organizations involved. We recognize that embracing change can be challenging, especially across a complex system of entities, and that DOE has already made important efforts toward many of these goals. However, we believe adoption by DOE of the recommendations contained in this report as core principles of all future efforts is crucial if the nation is to make timely progress in developing a nuclear waste management program to effectively address the nuclear waste issue.

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United States
Nuclear Waste Technical Review Board
2300 Clarendon Boulevard
Suite 1300
Arlington, VA 22201

(703) 235-4473
www.nwtrb.gov