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February 7, 2003

Mr. Martin Virgilio
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Dear Mr. Virgilio:

Please find enclosed 10 copies of the report *One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste*. Hard copies are also for sale and can be viewed electronically at the National Academies Press website: www.nap.edu.

Best regards,

Barbara Pastina

Barbara Pastina
Study director

NMSS06

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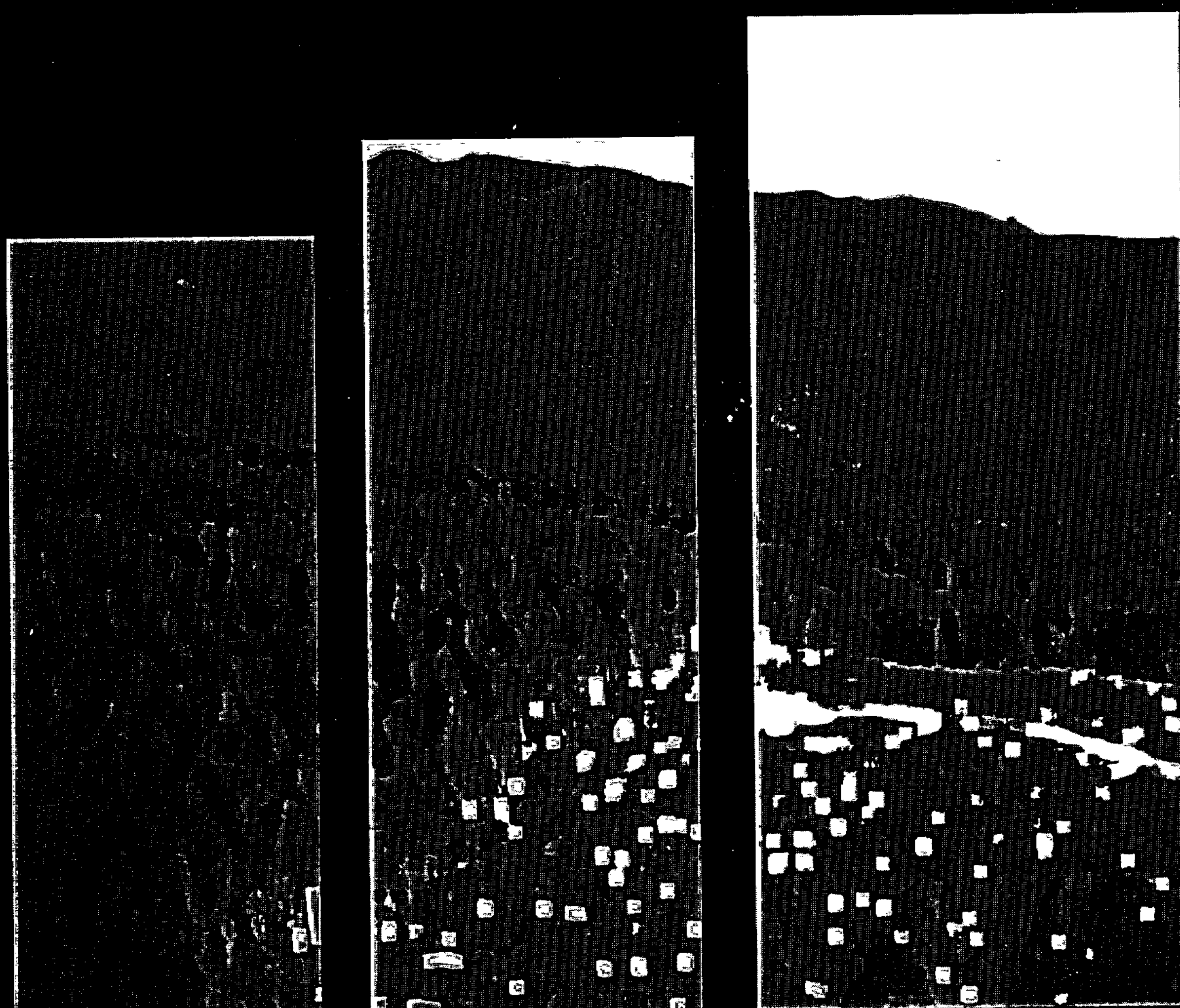
ONE STEP AT A TIME

The Staged Development of Geologic Repositories for High-Level Radioactive Waste



NATIONAL RESEARCH COUNCIL
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ONE STEP AT A TIME

The Staged Development of Geologic Repositories for High-Level Radioactive Waste

Committee on Principles and Operational Strategies for Staged Repository Systems

Board on Radioactive Waste Management

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Support for this study was provided by the U.S. Department of Energy under cooperative agreement number DE-FG08-97NV12056. All opinions, findings, conclusions, and recommendations expressed herein are those of the authors and do not necessarily reflect the views of the U.S. Department of Energy.

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Cover: The development of geologic repositories for the disposal of high-level radioactive waste presents technical and societal challenges. As is the case for other first-of-a-kind and complex projects, repository programs should proceed in stages, or steps, as recognized in waste disposal programs worldwide.

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THE NATIONAL ACADEMIES

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BOARD ON RADIOACTIVE WASTE MANAGEMENT

Preface

Recent decades have witnessed a continuing worldwide debate on the management of radioactive high-level waste,[1] and recent developments, including both major advances and setbacks, in various countries have led to an intensification of this debate. Geologic disposal involves placing high-level waste in a carefully selected, deep underground repository, where it remains isolated from the accessible environment for very long time periods until the waste no longer represents a hazard to humans or to the accessible environment. Disposal in a carefully sited and designed geologic repository is recognized by most of the international technical community, including the National Research Council, as a long-term management option for high-level waste that provides a high degree of safety and security (NEA, 1991, 1999a,b; NRC, 1957, 2001). However, geologic disposal of high-level waste has proven to be a major challenge for many nations. Delays and setbacks have been common, often attributable to the difficulties of simultaneously addressing technical and societal challenges (NRC, 2001).

Previous National Research Council committees have recommended a staged, or stepwise, approach for geologic disposal programs to address these technical and societal challenges (NRC, 1990, 2001). The 2001 National Research Council report *Disposition of High-Level Waste and Spent Nuclear Fuel* concluded:

> "For both scientific and societal reasons, national programs should proceed in a phased or stepwise manner, supported by dialogue and analysis" (NRC, 2001; p. 5).

Other international organizations, such as the Nuclear Energy Agency (NEA), and the International Association for the Environmentally Safe Disposal of Radioactive Materials (EDRAM),[2] also observed:

> "There is a general common trend towards advocacy of prudent, stepwise approaches at the implementational and regulatory level to allow smaller incremental steps in the societal decision making process" (NEA, 1999a; p. 11).

and suggested:

> "The stepwise approach could be a way to solve the problems involved in the implementation of radwaste [radioactive waste] management. It consists of a process where discrete and explicit steps are taken in repository planning and where the possibility of public input to the process is clearly stated. By increasing the transparency of the decision-making process, any counter-productive effects of public participation programmes may be avoided" (EDRAM, 2002; pp. 13-14).

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[1]In this report the term "high-level waste" includes defense-related high-level radioactive waste from reprocessing nuclear fuels, commercial spent nuclear fuel if it is considered to be a waste, and other nuclear materials designated for disposal along with reprocessing waste and spent nuclear fuel.

[2]This association comprises organizations (private companies and governmental agencies) responsible for radioactive waste management from 11 countries: Belgium, Canada, Finland, France, Germany, Japan, Spain, Sweden, Switzerland, the United Kingdom, and the United States.

Other review groups set up independently of implementers and regulators have also recommended a staged approach to repository development (EKRA, 2000; AkEnd, 2002).

As the U.S. Department of Energy (DOE) approaches a license application for Yucca Mountain, it faces some significant choices with respect to the design and operation of a repository. Because the Yucca Mountain repository would be a first-of-a-kind engineering project, DOE is considering a staged approach for its design, construction, operation, and closure. That is, DOE would make decisions about the repository in a stepwise fashion, commensurate with the available level of technical and policy understanding, and in a manner that allows for subsequent reversal, if warranted.

Although the concept of repository staging is receiving increased attention in many national waste disposal programs, including the Yucca Mountain Project, it is not well understood in an operational sense, nor has its implementation been considered in much detail.

Therefore, the DOE's Office of Civilian Radioactive Waste Management asked the National Research Council for advice on operational strategies for the development of a geologic repository for high-level waste. In the letter requesting this study, DOE wrote:

> "I believe that it would be very helpful to have advice from the National Research Council on strategies the Department [of Energy] could pursue for staging the design, construction, operation, and closure of a repository in a safe, secure, cost effective, and societally acceptable fashion. ... Although the concept of repository staging is receiving increased attention by repository programs in the United States and many other countries, it is not well understood in an operational sense. ...
> The potential benefits of staging, however, are very clear. From a technical perspective, staging provides opportunities for continuous learning and improvement over the life of a repository program. From a societal perspective, staging can provide for safe and secure waste disposal while also providing assurance to society that a system of checks and balances is in place to detect problems so that timely corrective actions can be taken if needed" (Itkin, 2000).

This report provides a systematic framework for a particular stepwise approach for repository development, termed "Adaptive Staging" (see Chapter 2), together with operational suggestions on how this approach can be applied in practice.

Acknowledgments

This report has been reviewed in accordance with the procedures of the National Research Council and reflects the consensus of the committee.[3] The report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. This independent review provides candid and critical comments that assist the National Research Council both in making the published report technically sound and in ensuring that the report meets National Research Council institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their participation in the review of this report:

[3]The National Research Council's Committee on Principles and Operational Strategies for Staged Repository Systems (see Appendix A).

John F. Ahearne, Sigma Xi, and Duke University
Roger E. Kasperson, Stockholm Environment Institute
Yves Le Bars, French National Agency for Radioactive Waste Management
Kai N. Lee, Williams College
Arjun Makhijani, Institute for Energy and Environmental Research
Sören Norrby, Swedish National Council for Nuclear Waste
Frank L. Parker, Vanderbilt University
Mary Lou Zoback, U.S. Geological Survey

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Paul B. Barton, Jr., U.S. Geological Survey, Geologist Emeritus, and John Applegate, Indiana University School of Law. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with National Research Council procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the National Research Council.

This study could not have been completed without the assistance of many individuals and organizations. The committee thanks DOE staff members from the Office of Civilian Radioactive Waste Management, the Yucca Mountain Project, national laboratories, and contractors, as well as staff of the U.S. Nuclear Regulatory Commission, State of Nevada, Nuclear Energy Institute, and numerous international and national experts for contributing to lively discussions and providing insights into the committee's task. In particular, the committee thanks all speakers at the information-gathering meetings (see Appendix B). The committee is especially grateful to the following staff members of the Office of Civilian Radioactive Waste Management: Jeffrey Williams, the committee's liaison, for his help and support in the committee's activities; Ivan Itkin and Lake Barrett, former director and acting director, respectively, and Margaret Chu, present director, for their interest in, and commitment to, this study.

The committee also thanks the National Research Council staff who helped initiate and steered this project. Barbara Pastina directed the study in a manner that was most productive, effective and efficient. Without her enthusiasm and drive, her ability to produce and edit text, and her personal skills in communication, this difficult task may well have proved impossible. Throughout the project, Barbara was ably assisted by Darla Thompson for research, and by Latricia Bailey (who also guaranteed that a very special product—a baby—would emerge from this study), Toni Greenleaf, James Yates, and temporary staff for administrative tasks. The Director of the Board on Radioactive Waste Management, Kevin Crowley, provided staff and the committee with constant encouragement, guidance and support, as well as specific valuable advice.

Finally, at a personal level, the Chair and Vice-Chair would like to thank all individual members of the committee. Long discussion sessions, longer writing sessions, yet longer conference calls and over 1,500 e-mails testify to the effort that has been put in by all. We have been working in a controversial area. A wide spectrum of views is present in the committee itself and we have a responsibility to present the equally wide spectrum of other stakeholder opinions. We have been working at a sensitive time in the repository program of the United States, so that every statement made by the committee may be subjected to a range of interpretations. This has increased the pressure on the committee members. It is gratifying that friendships have not been lost or weakened by

this, but rather made and strengthened throughout the one and a half years of this project. It has been a rewarding learning experience for us all.

Charles McCombie, Chair
David Daniel, Vice-Chair

Contents

Executive Summary

Compared to other large engineering projects, geologic repositories for high-level waste present distinctive challenges because: 1) they are first-of-a-kind, complex, and long-term projects that must actively manage hazardous materials for many decades; 2) they are expected to hold these hazardous materials passively safe for many millennia after repository closure; and 3) they are widely perceived to pose serious risks. As is the case for other complex projects,[1] repository programs should proceed in stages.

Recognizing the potential benefits of staging in managing a geologic repository program, the Department of Energy (DOE) asked the National Research Council for advice on how to implement staging during the construction, operation, closure, and post-closure phases of repository development. This study provides a discussion of the meaning of repository staging focusing specifically on programmatic, safety, security, institutional, regulatory, and societal factors. The report addresses staging primarily as applied to a generic repository program with applications to the U.S. program at Yucca Mountain (the Yucca Mountain Project).

The statement of task is broad, in that it required the examination of scientific, technical, policy, and societal issues. The project management recommendations in this report are based upon the combined judgment and expertise of committee members rather than on direct experience with implementation of staged approaches. The committee believes that the approach recommended will increase the likelihood of repository program success (as defined in Section 1.2.2) because it is consistent with accepted principles of sound project management and good engineering practices.

To address the statement of task, the committee identified two approaches for staging complex projects: Linear Staging and Adaptive Staging. Linear Staging and Adaptive Staging are not new concepts; both approaches have common features and there may be a continuum of approaches.

- **Linear Staging** is defined as a management process characterized by a single, predetermined path to a selected, well-defined end point, where stages are defined principally as milestones at which costs and schedules are reviewed and modified as necessary.
- **Adaptive Staging** is a management process characterized both by specific attributes (see Section 2.3) and by a formal and deliberate decision-making process (see Section 2.4). This process occurs between stages of project implementation and is intended to guide the implementer in identifying program improvements with respect to, for instance, safety, environmental impacts, costs, and schedules. Adaptive Staging provides a flexible but sound reference framework so that the ultimate path to success and end points themselves are determined by knowledge and experience gathered along the way.

[1]This report discusses examples of other complex projects, such as space missions, in Section 2.5.

Adaptive Staging is a cautious and deliberate decision-making and management process, fully consistent with good engineering practices. It emphasizes continuous learning, both technical and societal, includes 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.

When Adaptive Staging is employed, options for paths and end points remain open for as long as practical. Eventually, Linear and Adaptive approaches converge to an end. The final path, however, is usually not the one initially planned so that regulators, stakeholders, and the general public may perceive changes in the program as a reaction to some failure in the original plan. Adaptive Staging has the potential to reduce this perception by acknowledging remaining uncertainties and recognizing unexpected outcomes and occurrences as learning opportunities to improve the system.

Adaptive Staging is characterized by seven attributes. These are: commitment to systematic learning, flexibility, reversibility, auditability, transparency, integrity, and responsiveness. Taken separately, these attributes do not constitute the process that the committee calls Adaptive Staging; the simultaneous presence of these attributes makes the staging process truly Adaptive.[2]

The decision-making process separating stages is referred to as a "Decision Point." A Decision Point is not just a "point" in time, but a process involving analyses, review, and evaluations, as well as the consequent decisions for future actions. Thus, at a Decision Point, the program implementer initiates a process that:

1. systematically gathers, synthesizes, evaluates, and applies the information acquired to date;
2. develops options for the next stage, including explicit consideration of reverting to an earlier stage;[3]
3. evaluates and updates the assessment of the safety of the repository system, in light of the options;
4. makes the findings publicly transparent and available;
5. engages in dialogue with stakeholders;
6. decides on the next stage based on all of the above; and
7. disseminates decisions and their rationale.

In practice, the program implementer makes many more decisions than those at formal Decision Points. However, the more important or far-reaching the decision, the more the decision-making process resembles the Decision Point described above.

The main reason to plan these Decision Points throughout the program is to ensure that a series of relatively small decisions, each made on narrow criteria, does not lead the program onto an unsound path. Decision Points can also be introduced whenever new information warrants. Figures 2.1a, b, and c illustrate schematically

[2]The reader should not infer from this report that Linear Staging, by default, lacks all attributes of Adaptive Staging. A key difference between the two approaches is that Adaptive Staging is designed to fulfill all of these attributes, whereas that is not necessarily the case with Linear Staging.

[3]Because reversibility is always an option, it is important that the repository program provide flexibility in its reference framework.

the committee's view of the overall Adaptive Staging process, of an implementation and operational stage, and of a Decision Point.

While Adaptive Staging calls for a measured pace of program development and implementation, its objective is not to delay the program but to assure careful consideration of what is being learned and to focus on program progress rather than on meeting pre-arranged rigid milestones. Adaptive Staging does not require program "stops" at each Decision Point. Decision Points can be folded into the schedule so that, when a program is proceeding well, no undue delays are required. A Decision Point can be conducted in parallel with implementation (see Sections 4.2.2 and 4.5). Adaptive Staging emphasizes the iterative re-evaluation of the safety of the repository system throughout program development.

Adaptive Staging defines roles and mechanisms of interactions for all parties (implementer, regulator, stakeholders, and the general public) involved in the program. From the beginning, these parties must be aware of the definition of program success, acknowledge that there may be a number of unresolved issues at each stage, and recognize that program adjustments may result as knowledge is improved.

ES.1 Generic findings on Adaptive Staging

The most important findings are highlighted below; details are given in Chapter 6, supported by discussion in Chapters 4 and 5.

1. Adaptive Staging offers a promising approach to successful repository development (Sections 6.1 and 6.2).

The committee defines a successful repository program in Section 1.2.2. A successful *repository program* is different from a successful *repository*. Success of the *repository itself* will be known only far into the future, after thousands of years have passed without significant release of radionuclides into the accessible environment. The committee's definition of a successful *program* emphasizes the goal of achieving the required degree of technical and societal consensus to begin waste emplacement and the incremental improvement of waste emplacement operations.

The committee developed a set of generic and interrelated criteria that indicate whether a project is more likely to achieve success using Adaptive Staging (see Section 2.5). If a project satisfies most of these criteria, the committee believes that an Adaptive approach may be less error-prone, and thus more efficient, than Linear strategies, which have encountered serious obstacles when used in the development of geologic repository programs (see Section 2.8).

2. Effective Adaptive Staging involves the entire waste management system (Section 6.3).

Adaptive Staging has an impact not only on repository operations, but also on transportation, buffer storage[4] at reactor and repository sites, and on interim stor-

[4]For a definition of buffer storage, see the glossary (Appendix G).

age elsewhere (see Sections 4.2, 4.3, and 4.4). To achieve the flexibility required for Adaptive Staging, sufficient buffer storage must be available for repository operations, and the requirements for buffer storage must be planned in advance.

3. Adaptive Staging will not have any major negative impacts on security (Section 6.3).

It has been argued that the security of nuclear materials is easier to ensure if they are emplaced deep underground; thus, those materials should be emplaced in a geologic repository as soon as they are ready for disposal. Adaptive Staging may slow the initial pace of underground waste emplacement and, therefore, it may lead to longer periods in which the waste is more accessible to humans. Independently of the management approach chosen, the time that will elapse before geologic repositories will begin to operate is so long (i.e., decades) that other, more immediate, measures are needed to prevent misuse of radioactive materials by terrorists. Therefore, Adaptive Staging will not significantly impact the safe and secure geologic disposal of nuclear materials.

4. Iteration of the safety case is central to Adaptive Staging for geologic repositories (Section 6.4).

The committee addresses safety using the term "safety case," in accordance with growing international practices, to mean the integrated collection of all arguments that the implementer produces to demonstrate safety of the repository to all interested parties. Iterative assessment of the safety case is the fulcrum around which decisions are made. This means that the safety case is used in Adaptive Staging as a management tool to guide the implementer's actions during repository development. The safety case is also used to develop a program with features such as robustness and conservatism and to convince the implementer itself, the regulator, stakeholders, and the general public that there is a sensible and defensible set of arguments showing that the repository will be safe.

The safety case includes not only the quantitative analyses contained in a performance assessment (see Sidebars 2.1 and 5.1) but also a complete analysis of data and uncertainties in the assessment of repository performance, including supporting insights based on other independent lines of evidence, such as historical or natural analogs. Furthermore, to make the safety case more transparent to all stakeholders and the general public (see Sidebars 3.2 and 5.2), it should include an understandable explanation of how safety is achieved, and a similar discussion of the uncertainties that result from limitations in the scientific understanding of system behavior.

5. Adaptive Staging requires continuous and active learning in both technical and societal fields (Section 6.5).

The commitment to systematic learning is reflected in an on-going program monitoring the engineered and natural barriers of the repository system. A concurrent long-term science and technology program is also established to analyze and interpret the system's physical and operational behavior; recommend system improvements in response to new information; and address knowledge gaps. The long-term science and technology program should include relevant social science research to enhance the understanding of societal and institutional aspects of program development.

6. Adaptive Staging encourages opportunities for interactions with stakeholders and the general public (Section 6.6).

Stakeholder input to the decision-making process is of paramount importance for effective implementation of Adaptive Staging. Adaptive Staging encourages and explicitly calls for interaction with stakeholders and the general public at Decision Points (see Figures 2.1a, b, and c). Such involvement holds the potential for advancing social science knowledge and for enhancing public trust. Complete trust is not a prerequisite for Adaptive Staging; however, some trust is required to initiate this approach because the flexibility attribute of Adaptive Staging implies that end points and paths are not rigorously defined at the outset of the program. If stakeholders recognize their right to provide input to program decisions, they may be more likely to acknowledge the benefits of Adaptive Staging, may develop greater trust in the implementer and the process, and may acquire more confidence in the safety of the repository.

7. Adaptive Staging can be compatible with current regulatory systems (Section 6.7).

For Adaptive Staging to be effective, the regulatory system must include a license amendment process that is not overly complex or long and that allows the program to continue, if justified, during the amendment process. Adaptive Staging also provides a useful and continuous opportunity for stakeholder interaction with the regulator.

ES.2 Additional findings relevant to the U.S. program

The previous findings are generic, applicable to any repository program, including the Yucca Mountain Project. The following are additional findings specific to the U.S. repository program (details are provided in Chapters 5 and 6).

1. DOE has recognized potential advantages of staging (Section 6.8).

DOE has recognized the advantages of staging the development of the Yucca Mountain repository program and its current activities and plans satisfy some key attributes of Adaptive Staging: for example, stakeholders have access to a great amount of documentation and information. DOE is also in the process of introducing other changes in its program consistent with Adaptive Staging, the obvious examples being the increased emphasis on a potential pilot stage (see Appendix F, Section F.1.4), the development of a safety case approach (see Section 5.1.1), and demonstrating the feasibility of waste retrieval (see Section 5.1.3). However, DOE's approach remains essentially Linear (Sections 5.2 and F.2).

2. The U.S. regulatory system allows for Adaptively Staged development (Section 6.8).

The U.S. licensing process already follows a staged approach. The current U.S. licensing system requires DOE to submit applications for licenses before major phases of construction, waste possession and emplacement, and repository closure. Each license application must be supported by safety analyses based on a complete repository containing the full inventory of waste. The regulator, the Nuclear Regulatory Commission, expects the license application to be "as complete as possible in light of information that is reasonably available at the time of docketing" (66 Federal Register, p. 55739). This implies an expectation that additional relevant information will become available and be used as the project develops.

The regulator can impose licensing conditions and review and grant license amendments, which is consistent with Adaptive Staging. It is expected that the initial license application will be sufficiently conservative to provide adequate margins of protection to account for uncertainties in expected repository performance. Should information that justifies modifications to the reference framework be obtained during early stages, program adaptations would be carried out through subsequent modifications to the safety analysis and then through license amendments.

The iterative review of the repository safety case called for in Adaptive Staging is also compatible with the regulatory process. The Nuclear Regulatory Commission does not use the term "safety case" for the analysis of post-closure safety (which is of most relevance here), but the applicant is required to carry out a performance assessment and a safety analysis. Regulations describe specific requirements for the safety analysis (see Title 10 of the Code of Federal Regulations Part 63.114) and these are broadly similar to the safety case concept described by the committee. When one compares requirements for the safety analysis with the characteristics of the safety case, a similar set of technical issues is addressed in each. Therefore, the primary differences between a safety analysis and Adaptive Staging's safety case are that the safety case will be reviewed at every Decision Point and that it presents key safety arguments in a manner accessible to a wider audience. This accessible presentation of safety arguments is not necessary for the regulator, due to its technical expertise, who can make its judgment on repository safety based on the quantitative and qualitative compliance requirements in the regulations.

ES.3 Specific impacts of Adaptive Staging on the U.S. program (Section 6.9)

Specific changes would result from implementing Adaptive Staging in the U.S. repository program. If adopted, Adaptive Staging would lead DOE to do the following:

- Highlight the goal of ensuring safety and security at all times more prominently than the specific milestone of emplacing 70,000 metric tons of heavy metal in Yucca Mountain.

- Focus more strongly on achieving the degree of technical and societal consensus needed to begin waste emplacement, rather than on the emplacement of all waste.
- Introduce stages that explicitly focus on what can be learned about safety (i.e., re-evaluating the safety case) and about concerns by the regulator, stakeholders, and the general public.
- Start conservatively in design and operations, with the opportunity to reduce conservatism as new knowledge allows.
- Plan for early pilot and test facilities along with possible demonstration facilities; clarify with the Nuclear Regulatory Commission how the use of these facilities could affect the licensing process.
- Focus specifically on assuring and demonstrating retrievability.
- Focus on explicit thermal load management alternatives.
- Plan for sufficient buffer storage at or near the site, with transparency about its policy implications, and decouple the rate of waste acceptance from the rate of waste emplacement underground.
- Place high priority on defining and securing funding for the monitoring and the science (including social science) programs with the intention of modifying and improving the programs as learning progresses.

ES.4 Generic recommendations on Adaptive Staging

The following are generic recommendations for any geologic repository program (Section 6.10).

1. Adaptive Staging should be the approach used in geologic repository development.

The committee believes that Adaptive Staging is likely to be more effective and less error-prone in repository development than Linear Staging or similar approaches. It recognizes, however, that given the large uncertainties and challenges involved, no management approach can guarantee a successful repository or a successful repository program as defined in Section 1.2.2. Adaptive Staging may also require the implementer to make cultural and organizational changes if this approach is to succeed. For instance, learning will be minimal unless the implementer actively seeks out alternative viewpoints, openly acknowledges errors and uncertainties, specifically addresses societal issues, and organizes and undertakes relevant research to improve the knowledge base.

The long time scale of repository operation implies that organizational performance needs to be maintained over decades and possibly centuries. Stability on this order is not the norm in corporations or governments. Hence, lessons of successful organizations and transferability of these lessons are useful areas of study. Adaptive Staging is clearly helpful with technical matters, but it can also help the program accommodate to changing political factors. While there are opportunities for implementing Adaptive Staging throughout the program, these are especially numerous in early stages and when repository closure decisions are made.

2. A repository program should be based on a structured decision-making process that places emphasis on iterative review of safety for the entire repository system.

One essential feature of Adaptive Staging is the periodic re-evaluation of safety at Decision Points to guide the program. The committee believes that the safety case, as described in this report, is an appropriate tool for implementing this re-evaluation. A periodic re-evaluation of the safety case at each Decision Point allows the implementer to improve the robustness and reliability of the entire repository system, identify and resolve safety issues, incorporate new knowledge, and address other issues of concern raised by the regulator, stakeholders, or the general public.

3. The repository program should make full use of learning opportunities offered by *in situ* testing.

Adaptive Staging takes advantage of the learning opportunities during the buildup to full-scale implementation for improving operations, enhancing safety, or both. Examples of learning opportunities for *in situ* activities include:

- construction of a pilot facility for trials aimed at learning how operations can be most efficiently and safely performed;
- implementation of a test facility for short- and long-term scientific research aimed at reducing residual uncertainties and improving performance in key areas; and
- use of a demonstration facility for raising the confidence of stakeholders and the general public in the safety of the actual repository operation and to allow comprehensive monitoring of specific system components.

If the implementer decides to use pilot, test, and demonstration facilities, the repository initial license application should contain provisions to implement these facilities.

4. The repository implementer should ensure a continuous and active learning process.

During the decades of repository operation it is prudent, and it will be expected by the public, that the implementer continues to analyze whether initial safety assumptions remain valid and also continues to improve the system. To support this learning, repository programs should have:

- a broad, comprehensive, long-term science and technology program that continues throughout the lifetime of repository operations; is targeted and accountable, peer-reviewed, and of sufficient breadth to address key knowledge gaps, including those in social sciences; and also defines learning objectives for each stage;

- a monitoring program that collects scientific, technical, and societal data from appropriate sources; and
- a "performance confirmation" program[5] that focuses on the data acquisition and modeling that is directly related to those issues upon which the licensing and the safety case are based, including performance assessment methodology testing.

5. The repository program should integrate independent technical advice and stakeholder input to the maximum possible extent.

Emphasis on a system of independent peer review is important. The implementer should encourage the establishment of a technical oversight group that also includes a social science component and is independent of the government to provide an independent technical analysis and to provide advice on the repository development program. Separately, a stakeholder advisory board consisting of representatives from institutional stakeholders and other stakeholder groups—such as local institutions, local and affected governments, universities, as well as representatives from industry, non-profit, and labor organizations—should provide additional input on stakeholder concerns, establish a venue for regular dialogue and consultation, and take part in Decision Points (see Section 4.2).

ES.5 Specific recommendations for the U.S. program

The following are additional recommendations, specific to the U.S. program, and take into account the national context and constraints imposed on DOE (Section 6.11).

1. DOE should adopt Adaptive Staging.

To address the challenges it is facing, DOE should align itself with Adaptive Staging. DOE would then be better positioned to formalize the learning process and to address broader technical and societal issues while building stronger public trust. For example, the safety case that DOE is planning to produce should include a description of safety arguments understandable by the general public that would be re-evaluated at all major Decision Points. Adaptive Staging envisions many more Decision Points than decisions to apply for licenses. The corresponding intentions and actions concerning the use of Adaptive Staging should be communicated to and discussed with stakeholders. DOE should also communicate the criteria it uses for judging the success of each stage and for deciding whether to change or even to reverse the course of actions. The committee believes that there are substantial opportunities for DOE to implement Adaptive Staging if it decides to adopt this strategy. The sooner Adaptive Staging is adopted, the more effective it likely will be.

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[5]For a definition of performance confirmation program, see Appendix G.

2. DOE should implement *in situ* pilot and test activities and should examine the possibilities for demonstration activities.

The committee recommends the introduction of a pilot stage designed to maximize systematic learning opportunities in the Yucca Mountain Project. The pilot stage could consist of emplacing first non-radioactive simulated waste and then a small fraction of radioactive waste in a section of the repository (the latter after the appropriate license is received). The purpose of this pilot stage is to gain experience with, for example, handling different waste types, emplacing waste packages and backfills, and choosing thermal operating modes. DOE should expand its knowledge outside the bounds of the pilot stage by performing in parallel *in situ* test activities. The objective is to develop a better understanding that could lead either to improved confidence in isolation or to better methods of repository implementation. DOE should also examine, in collaboration with stakeholders, the potential benefits of reserving a fraction of the waste disposal area for demonstration purposes.

3. DOE should set up an independent technical oversight group and a stakeholder advisory board.

The scientific work in the program must be—and must be recognized to be—subject to and responsive to independent input and review. The long-term science and technology program recently proposed by DOE[6] should be given appropriate institutional status and a stable, sustained level of commitment and funding. Social science research should be included as an integral part of this program. Possible roles of a stakeholder advisory board and technical oversight groups for the Yucca Mountain Project are discussed in Section 5.1.3.

4. Even if the U.S. program begins with a reduced-scale pilot stage, DOE should present a safety analysis and a safety case based on the full inventory.

If DOE decides to begin its repository program with a reduced-scale pilot stage, it should nevertheless present a safety analysis for the Nuclear Regulatory Commission and a safety case for stakeholders and the general public both based on a full-inventory repository.[7] A full-inventory safety analysis and a safety case are important in the United States, as in any waste disposal program, to help establish confidence by the regulator and by the general public, respectively, in the ultimate safety of the complete repository system envisioned.

5. DOE and the Nuclear Regulatory Commission should work together (without compromising their independence) to ensure that the regulatory process

[6]DOE's long-term science and technology program, which began in April 2002, is currently being organized (Nuclear Waste News, 2002).

[7]The Nuclear Regulatory Commission already requires DOE to present a full-inventory safety analysis to license the construction of a geologic repository.

enables the application of Adaptive Staging in the development of the Yucca Mountain project.

The committee believes that the regulatory framework contains adequate flexibility to accommodate Adaptive Staging if the regulator supports this approach. DOE should take the initiative to demonstrate the benefits of Adaptive Staging to the USNRC. DOE and the regulator should consider the potential interaction of Adaptive Staging and the regulatory process, including procedures for license amendments. In particular, the USNRC and DOE should have a common understanding of which changes, tests, and experiments can or cannot be made without advance regulatory approval. The USNRC has already identified some changes, tests, and experiments that can be made without advance regulatory approval and has provided decision criteria for these. The USNRC and DOE should consolidate and coordinate broad access to information and stakeholder participation as well as evaluate opportunities to improve the current practices of DOE public hearings and USNRC licensing actions. Transparency and stakeholder oversight would ensure the independence of the regulating and the regulated institutions.

6. DOE should consider the impact of Adaptive Staging on the overall waste management system.

DOE should ensure that there is an adequate understanding of the impacts that Adaptive Staging can have on the overall waste management system. Early, full, and transparent consideration must be given for understanding the implications of the staging process on all of these system components, in particular concerning requirements for buffer storage.

7. DOE should continue to actively promote a safety culture throughout the long duration of the Yucca Mountain Project.

Adaptive Staging is consistent with the considerable effort that has been devoted to developing a safety culture in the nuclear arena (Section 4.8). Standard 14001 of the International Standards Organization (ISO), evaluating environmental management systems, has important principles in common with Adaptive Staging. The ISO Standard 14001 (implemented in other DOE facilities, such as the Waste Isolation Pilot Plant) may be an additional useful vehicle for enhancing the safety culture within the Yucca Mountain Project.

ES. 6 Concluding remarks

The committee debated at great length the originality of Adaptive Staging and the confidence with which it can advocate this approach as beneficial for waste disposal programs in the United States and elsewhere. To the first point, it is important to note that the term Adaptive Staging is used basically as shorthand for a collection of project management components, none of which is new or unique to this approach. Most of the components are to be expected in any major, well-managed project. The committee uses a new term (Adaptive Staging) to emphasize that *all* of the components should be applied simultaneously within a particular institutional culture that encourages continuous learning and that uses iterative review of system safety as the principal guiding mechanism.

In discussions about how strongly the committee could advocate the approach described, two opposing arguments recurred. The committee agreed that Adaptive Staging is a prudent approach, in line with the normal tenets of good project management, and can lead to program improvements. The committee recognizes, however, that these improvements will occur only if the implementer's organizational culture allows changes, and it acknowledges that this approach is untried.

These counterbalancing arguments lead to the cautious caveats applied to the committee's recommendations but should not detract from the consensus reached: because of the distinctive challenges faced in developing a geologic repository program (see Section 1.2.1), and the context in which these must be addressed (see Sections 2.5, 3.1, and 3.2), Adaptive Staging enhances the likelihood of program success.

1

Introduction

The objective of this study is to advise the Department of Energy (DOE) on how to implement a staged geologic repository program for high-level waste.[1] The Nuclear Energy Agency has defined a staged approach to repository development as a process involving:

> "discrete, easily overviewed steps [that] facilitate the traceability of decisions, allow feedback from the public and/or their representatives, promote the strengthening of public and political confidence in the safety of a facility along with trust in the competence of the regulators and implementers[2] of disposal projects" (NEA, 1999a, p. 11).

The staging concept embodies a more flexible approach to repository development, consistent with recommendations from a previous National Research Council report (NRC, 2001) on the disposition of high-level waste, and reflects current consensus in the international radioactive waste management arena (NEA, 1999a,b; EDRAM, 2002). The 2001 National Research Council report also emphasizes the enhanced learning opportunities available in a staged approach.

1.1 Statement of task

The statement of task is presented in Sidebar 1.1. Sections of this report addressing specific points of the statement of task are indicated in parenthesis. As requested, the committee focuses primarily on operational aspects of a geologic repository program; however, early in the committee's deliberations the study's scope was broadened. It was recognized that staging addresses the entire geologic repository program, beginning with siting and continuing to the post-closure phase.

The statement of task is broad, in that it requires the committee to examine policy and societal issues as well as science and technology matters. Given that managing the repository development process is a new challenge, with few or no past analogues, project management recommendations in this report are based upon the combined judgment and expertise of committee members rather than direct experience with implementation of staged approaches.

[1]In this report the committee uses the term "high-level waste" to include defense-related high-level radioactive waste from reprocessing nuclear fuels, commercial spent nuclear fuel, if it is considered to be waste, and other long-lived radioactive materials designated for disposal in geologic repositories.

[2]The implementer of a disposal concept is the institution responsible for managing the radioactive waste program. See also the glossary, Appendix G.

SIDEBAR 1.1 Statement of Task

The National Research Council will provide recommendations on the design and operational strategies for a staged geologic repository. These recommendations should address the following points in a generic sense, with applications to the Yucca Mountain Project where appropriate:

1. The technical, policy, and societal objectives and risks for developing a staged repository system (Chapters 2 and 4).
2. Potential impacts of staging on pre- and post-closure safety (Section 4.8) and security (Section 4.9) as well as cost (Section 4.5), public acceptance (Section 4.11), and repository operations (Section 4.2).
3. Strategies for developing a staged repository system, including design strategies; strategies for constructing, filling, and closing a staged repository (Section 4.2); monitoring strategies to confirm repository performance during pre- and post-closure phases, including a consideration of what should be monitored and confirmed (Section 4.6 and Appendix E).
4. Identification of knowledge gaps that should be addressed to improve design, monitoring, and performance confirmation capabilities (Section 4.1 and Appendix E).
5. Identification of potential incompatibilities of a staged repository system with licensing procedures, and strategies for resolving them (Section 4.10).

However, the committee believes that the approach recommended in this report will increase the likelihood of repository program success (see Section 1.2.2) because it is consistent with accepted principles of sound project management and engineering practices.

1.1.1 Origin of this study

Recognizing the potential benefits of staging, DOE asked the National Research Council for advice on how to implement staging during the design, construction, operation, closure, and post-closure phases of a geologic repository program for high-level waste. To investigate the applicability of staging to generic geologic repository programs the National Research Council appointed a committee[3] of 14 members (see Appendix A). The present report builds on the 1990 and 2001 National Research Council reports on geologic disposal of high-level radioactive waste and expands on this committee's progress report released in March 2002 (NRC, 1990, 2001, 2002a).

[3] Committee on Principles and Operational Strategies for Staged Repository Systems.

1.1.2 Context of this study

When the committee began work in 2001, DOE was preparing to recommend the Yucca Mountain site in Nevada as a suitable site for a federal high-level radioactive waste repository. In February 2002, DOE submitted the site suitability recommendation to the President, who, in turn, submitted it to the U.S. Congress. Nevada subsequently vetoed the recommendation but Congress over-rode Nevada's veto. In July 2002, the President signed a resolution allowing DOE to apply to the Nuclear Regulatory Commission for a license to construct a repository at Yucca Mountain.

The political debate and the concomitant public awareness heightened sensitivity to the issue of geologic disposal of high-level waste in general, and to the congressional decision in particular. It is important to emphasize the limitations on the scope of the committee's statement of task (Sidebar 1.1). The statement of task does not direct the committee to comment on:

- the choice of geologic disposal as the preferred option for high-level waste management,
- the suitability of Yucca Mountain, Nevada, as a geologic repository site, and
- the specific siting decisions taken by DOE, the President, or the Congress.

As the statement of task requested, this study addresses a generic repository program with applications to Yucca Mountain, where appropriate.

1.1.3 Committee's strategy to address the task

The process leading to this report is summarized as follows. The delays (and rising costs) and impasses in the disposal of nuclear waste in nearly every radioactive waste management program has prompted various countries to reassess management approaches for the development of geologic repositories. One important concept emerged: A central feature of a new management approach might be to proceed in steps or stages (EDRAM, 2002; NEA, 1999a). This then became a widely shared informal hypothesis to be investigated and was suggestive enough that DOE asked the National Research Council for advice on how a staged approach might best be implemented. The committee's work can thus be characterized as a rigorous, collective analysis to assess the feasibility of the hypothesis. In its approach to address the statement of task, the committee:

- elaborates the concept of staged development for repository programs (hypothesis);
- identifies and adopts terms to describe alternatives that represent two distinct management approaches:
  - -Linear Staging: a single predetermined path, in which stages are defined primarily by milestones driven by program schedule, costs, and technical content, and

-Adaptive Staging: a flexible process based on incremental decisions, in which stages are predicated on the outcome of previous stages and are separated by structured Decision Points;[4]

- develops a list of attributes of Adaptive Staging;
- characterizes the decision-making process involved in the Decision Points; and
- addresses the following questions:
  -What type of project benefits from Adaptive Staging?
  -What rationale leads a repository program to use Adaptive Staging?
  -What potential benefits and drawbacks can result from Adaptive Staging?

As the committee addressed its task it quickly realized two things: first, given the large uncertainties and challenges of repository development, no management approach can guarantee a successful repository or a successful repository program as defined in Section 1.2.2. Second, again given the uncertainties and challenges, the development process needs to be resilient and incremental (i.e., adaptive). Therefore the committee suggests that as described in the following paragraphs, Adaptive Staging is likely to be more effective and less error-prone than Linear Staging or similar approaches.

1.1.4 Organization of this report

Chapter 1 presents the study's objective and task, the challenges of high-level waste geologic repository programs, and a definition of a repository program's success. Chapter 2 differentiates two types of staging, Linear and Adaptive, and discusses criteria for their applicability in program management. The remaining chapters discuss Adaptive Staging for geologic repository programs. Chapter 3 describes activities involved in repository development phases as well as the institutional and societal context of high-level waste geologic disposal. The programmatic, safety, security, institutional, regulatory, and societal impacts of Adaptive Staging are addressed in Chapter 4, along with knowledge gaps. The statement of task directs the committee to focus mainly on operational details. Therefore, an in-depth study of the societal and institutional ramifications of staging was judged to extend beyond the statement of task. Given the time constraint, the committee only addresses the initial impacts and identifies knowledge gaps in societal and institutional domains. Chapter 5 discusses Adaptive Staging in the context of DOE's Yucca Mountain Project and comments on the approach's applicability to the U.S. situation. Chapter 6 presents the committee's findings and recommendations, first for the generic case and thereafter specifically for Yucca Mountain. The appendixes elaborate on important issues raised in the main text. Appendix G provides a glossary of key terms.

1.2 A generic geologic repository program

A geologic repository program typically consists of the following phases:[5]

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[4]A Decision Point is not just a "point" in time, but a process involving analyses, reviews, and evaluations, as well as the consequential decisions for future actions. See Section 2.4

1. selection of specific geologic disposal option(s),
2. site selection and characterization,[6]
3. licensing,[7]
4. construction,
5. operation,
6. closure, and
7. post-closure.

The time frame for each phase varies considerably: from a few years to decades for selecting the geologic disposal option and the site; through several decades of operations, and up to centuries for the closure; and many thousands of years for the post-closure phase. Not all national repository programs include all these phases. The phases cited above are described in Chapter 3.

1.2.1 Challenges in the development of geologic repositories

Compared to other large engineering projects,[8] geologic repositories for high-level waste are peculiar undertakings because (1) they are first-of-a-kind, complex, and long-term projects that must actively manage hazardous materials during the operational phase; (2) they are expected, using natural and engineered barriers, to hold these hazardous materials passively safe for many millennia after repository closure; and (3) they are widely perceived to pose serious risks. These challenges are discussed briefly below.

- **First-of-a-kind.** There are no licensed geologic repositories for high-level waste in the world.[9] This untested status of high-level nuclear waste disposal systems creates technical and societal uncertainties. The principal technical uncertainties arise from the complexity of the geologic system and the impossibility of demonstrating at closure the safety of the repository over tens of thousands of years in the future (see Sidebars 1.2 and 1.3). The prediction of long-term behavior of natural and engineered barriers must rely on modeling rather than operational experience. In the presence of such uncertainties, unexpected discoveries are inevitable.
- **Complex.** "Complex" means composed of many interconnected parts. More than in other objectively complex, large-scale, engineered facilities, such as

[5]Phases are defined as main elements of a generic repository program. Phases can be divided into stages (see also the glossary, Appendix G).

[6]Of course, on-site research and monitoring activities to improve scientific understanding of the repository system continue beyond the site characterization phase.

[7]Licensing is not just one phase in the program, it is an ongoing process continuing throughout the repository program. The initial licensing phase includes selection of the repository design.

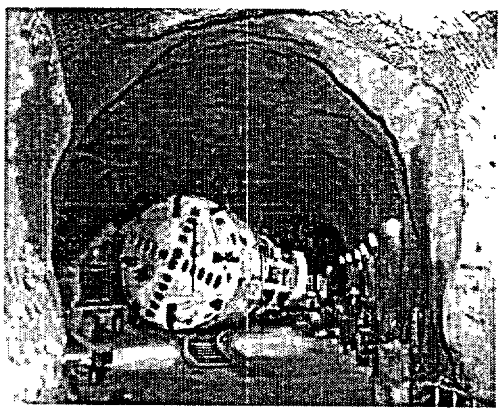
[8]This report discusses examples of other complex projects, such as space missions, in Section 2.5.

[9]Geologic repositories for other waste types have been implemented (e.g., low-level and intermediate-level waste in Scandinavia and transuranic waste at the Waste Isolation Pilot Plant in the United States), but highly active, long-lived, heat-generating waste has not yet been disposed of permanently.

space programs or modern chemical processing plants, geologic repositories are heterogeneous systems with natural and engineered components that require timely integration of scientific, technological, institutional, and societal processes.

• **Long-term.** Repositories present two long-term challenges: (1) program development and (2) safety demonstration. Program development (i.e., siting, constructing, operating, and closing a repository) takes at a minimum, several decades. It is difficult, if not impossible, to plan clearly and reliably to the end of such a project. A future generation will be charged with ending the project.

SIDEBAR 1.2 Is Building a Repository Different from Building a Large Dam?



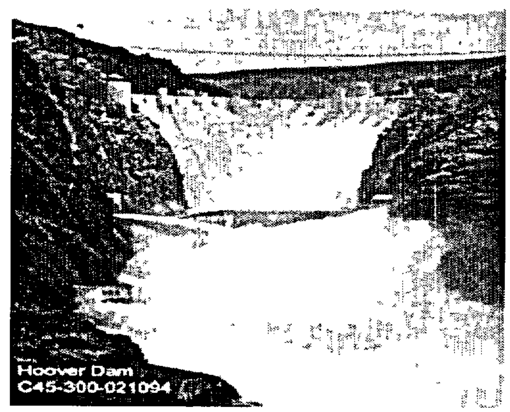


FIGURE 1.1 On the left, a picture of a tunnel and the tunnel-boring machine in the Experimental Studies Facility at Yucca Mountain, the proposed high-level radioactive waste geologic repository site in Nevada, United States. On the right, the Hoover Dam, Nevada.

Dams and repositories are both large public works projects that involve significant hazards. The two have selected challenges in common:

• They necessitate a cautious and prudent engineering approach to help ensure adequate safety. Both dams and repositories aim at a high degree of robustness, achieved in part through engineering over-design.

• They can result in major societal controversies, and increasingly do so. Dams were successfully built decades ago; today it is debatable whether a major dam could be built without controversy. Controversy also surrounds repository projects.

There are also important differences between the new challenges presented by repository development and the more familiar challenges of dam building:

• Society has a long history and much experience in building dams. Society has no experience building and operating a geologic repository for high-level radioactive waste.

- Dams are usually designed with life expectancies of tens of years. A geologic repository will be designed with a life expectancy of many thousands of years. This difference in time expectancies has technical and institutional implications.
- Dams are inspected regularly to confirm that the structures are within design specifications. Similarly, a performance confirmation program[a] for a repository is critically needed but must be designed and implemented for much longer time periods, and depends finally on assessments of future performance for very long time periods—without historical precedents.
- The failure[b] of a dam may be sudden and complete and its effects are obvious. The failure of a geologic repository will almost never be sudden and complete and it might be undiscovered for centuries.
- Dams and repositories both require detailed characterization of the near-field properties of the natural systems surrounding the site, so that flaws or weaknesses can be offset by engineering solutions. It is generally infeasible to characterize comprehensively the regional, deep-, and far-field properties of the natural environment. This uncertainty in geotechnical conditions at some distance from the dam would have a minimal impact on its integrity; however, for a geologic repository, this uncertainty may hide serious flaws in the natural barriers that are relied upon as the ultimate protection in the event of failure of a repository's engineered barriers.
- Dams are used and directly observable by the public as well as by scientists and engineers for monitoring over their entire life span; whereas after waste emplacement begins, a geologic repository will not be directly observable for most of its life span (i.e., after closure).
- Dams are designed to defeat nature and natural geologic processes. Geologic repositories are designed to take full advantage of nature and natural geologic processes.

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[a]For a definition of performance confirmation program, see Appendix G.
[b]Failure is used here to mean a failure of engineered components. Deliberate human intrusion or terrorist activities are not included as failure of the facility itself, but rather of the security and administrative oversight.

Although demonstrating repository safety over tens of thousands of years is impossible, a high level of confidence in future repository performance is essential because some radioactive waste remains hazardous for a very long time (up to millions of years).

- **Risk.** Handling high-level radioactive material entails risks. Two different aspects of risk influence implementation approaches: (1) the long life of radioactive waste means that a legacy of risk is passed on to future generations, and (2) the public perceives repositories as risky because of the well-documented public dread associated with nuclear technologies (Flynn et al., 1993).
- **Negative public image.** History and current events connect nuclear technologies with weapons and war. Nuclear fission, even before its use could be

harnessed and made practical, was viewed with deep ambivalence and great suspicion (Weart, 1988). Public distrust has expanded to the institutions managing nuclear technologies. This connection helps explain the negative public images associated with radioactive waste (Dunlap et al., 1993).

• **Controversy.** Many aspects of radioactive waste management are controversial, this controversy being often associated with the more general debate on nuclear energy. There is often little or no societal agreement on waste management goals, siting, disposing, transporting, securing, funding, and policy-making. All are issues on which strongly differing opinions are held. Controversy equally applies to ethical issues, such as societal values, institutional integrity, and inter- and intra-generational equity. The lack of agreement on program goals is a source of public skepticism or worse a basis for distrusting the institutions charged with formulating and implementing the specific policies (NRC, 2001).

A National Research Council committee previously addressed these technical and societal issues (NRC, 2001), that place special demands on the management approach. For example, the lack of precedent suggests the need for a management approach characterized by continuous learning and flexibility. Moreover, the decades-long development of a geologic repository requires a flexible approach that incorporates new knowledge as the program unfolds. An earlier report of the National Research Council on high-level waste management suggested a flexible approach that acknowledges the following premises:

> "Surprises are inevitable in the course of investigating any proposed site, and things are bound to go wrong on a minor scale in the development of a repository
>
> If the repository design can be changed in response to new information, minor problems can be fixed without affecting safety, and major problems, if any appear, can be remedied before damage is done to the environment or to public health" (NRC, 1990, p. 7).

In a flexible approach, confidence in the long-term safety of a geologic disposal system should be maintained or enhanced as the program evolves. This implies that assessing the impact on safety of any programmatic change becomes an important task to be performed iteratively throughout development. There is a developing international consensus (International Atomic Energy Agency [IAEA], 1997; NEA, 1999a, 2001a; NRC, 2002) that an appropriate "tool" for assessing confidence in the long-term safety of a geologic disposal system is preparation of a safety case, which is described in Sidebar 2.1.

Because of the first-of-a-kind nature and the controversy over goals, together with the real and perceived risks, the repository development program needs reversibility as long as feasible. Indeed, if alternative goals are to remain open as progress down a chosen path occurs, then reversibility is required for a program to be credible.

Sidebar 1.3 Using Words Carefully

All scientific and technical disciplines develop a specialized language with certain words or phrases becoming, for disciplinary experts, a type of shorthand for more complex concepts. Virtually all papers published in peer-reviewed journals contain language or jargon that may be misleading, ambiguous, or opaque to those not familiar with such discipline-specific usage. When the maintenance of confidence by a broad audience of stakeholders and the general public is essential, it becomes particularly important to communicate carefully and accurately in ways that make information accessible to parties beyond narrow experts speaking an insider language. This objective is of particular importance in the context of this study because geologic disposal programs are dependent upon a wide variety of scientific, technical, and analytical areas of expertise and because the proposed Adaptive Staging approach emphasizes the need for transparency and integrity.

The committee has had frequent detailed discussions throughout its deliberations about the meaning and potentially misleading usage of phrases such as "demonstrate safety" and "performance confirmation." As examples, both of these phrases have generally accepted and nuanced meanings when applied to repository development programs by specialists associated with the programs, but they can be misleading when used in communications with the broader community.

For many engineered systems a "demonstration of safety" can be achieved by repeated observations of their behavior over the operational lifetime. The concept takes on a different meaning when safety must be maintained over geologic time scales. The ultimate safety of a repository can be known only far in the future and the prediction of long-term behavior of natural and engineered barriers must rely on modeling rather than operational experience. Thus, "demonstration" here implies not absolute proof by observation but rather showing that one can have sufficient confidence in the models and their results.

Similarly, "performance confirmation" does not directly confirm long-term performance as only experience can but rather applies existing monitoring capabilities to evaluate whether previously made assumptions are consistent with measured results. The committee has tried to be clear when using such phrases, but notes that care needs to be taken by program participants when using these and many other phrases that may promise more than they can deliver.

Similarly, a previous National Research Council Report emphasizes the importance of demonstrating reversibility of actions:

> "Demonstrated reversibility of actions in general, and retrievability of wastes in particular, are highly desirable because of public reluctance to accept irreversible actions" (NRC, 2001, p. 3).

The complex framework of technical, societal, and institutional issues surrounding geologic repositories along with historical connections of radioactive waste to nuclear programs, often associated with secrecy and controversy, requires a management approach that demonstrates transparency, flexibility, integrity, responsiveness, and willingness to engage in a dialogue with all parties.[10] The recent report on geologic disposition of high-level waste recommended:

> "For both scientific and societal reasons, national programs should proceed in a phased or stepwise manner supported by dialogue and analysis" (NRC, 2001, p. 5).

1.2.2 Definition of a successful geologic repository program

What defines success for a geologic repository program? The repository implementer's focus is often on disposing of a set amount of waste in a set time for a set cost or having all the waste underground in a sealed repository. These answers do not fully account for the technical and societal challenges mentioned above, the long times over which the program will be developed, or the much longer time required for waste isolation.

First and foremost, the ultimate measure of success of a repository is the extent to which it isolates the waste from the accessible environment for all future time during which the waste remains hazardous. In the committee's view a more pragmatic and useful definition of success for the implementer focuses on a safe geologic repository that is also cost-effective,[11] follows an adaptable reference framework[12] rather than a rigid schedule, and is societally acceptable. More concretely and more measurably, the committee defines a successful geologic repository program as one in which:

- a geologic site and engineered system, judged to be technically suitable using the particular country's accepted regulatory, public, and political processes, have been identified;

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[10]The meanings of transparency, flexibility, integrity, and responsiveness, as well as willingness to engage in a dialogue with involved parties, are discussed in Section 2.3.

[11]In this context, "cost-effectiveness" refers to the operational phase of a geologic repository, i.e., when the repository is open. Like in most construction projects, cost-effectiveness means comparing options and choosing those that deliver the best product for a given cost, or improving the value of product performance enough to justify additional cost. The performance of the repository after its closure will not be determined for long periods, so only models and forecasts can be used to determine uncertainties and projected costs (see Sidebar 1.3).

[12]The reference framework of a repository program is the plan for developing a successful geologic repository. The reference framework is based on the best scientific and societal knowledge available at a given time. The reference framework includes, for instance, a reference repository design and a proposal for stages and decision-making process. The framework is not a rigid roadmap attempting to define all future activities to successful project implementation. At the end of each stage, the details of the reference framework may be adapted (i.e., the repository design and number of Decision Points may change) according to knowledge gathered along the way.

- operational and long-term safety aspects are made consistent with the current scientific understanding of repository systems; safety features are reviewed; and the necessary licenses are granted;
- an ongoing long-term monitoring and observation program designed to substantiate the current scientific understanding of the safety aspects of the repository system is in progress;
- sufficient societal consensus is achieved to allow operations to begin and continue;
- initial waste emplacement has taken place with plans for reversibility;
- all necessary safety and security measures are set up to emplace additional waste, if decided;
- procedures and funding arrangements[13] are agreed to for either:
  -backfilling (if used), closing, and sealing the repository[14] (if technical and societal confidence in its long-term isolation properties continues); or
  -maintaining capability for long-term control and monitoring, and capability for retrieving wastes, if waste retrieval is necessary for technical or societal reasons.

A successful repository program is different from a successful repository. Success of the repository itself will only be known far into the future, after thousands of years have passed without significant release of radionuclides into the accessible environment. The committee's definition of a successful *program* emphasizes the goal of achieving the required degree of technical and societal consensus to begin waste emplacement and the incremental improvement of waste emplacement operations, rather than moving rapidly to full-scale emplacement. Repository implementers often view a fast ramp to full-scale emplacement and rapid waste emplacement until the repository is filled as a measure of success (since they may be under pressure to rapidly accept waste for disposal). This is consistent with Linear Staging but not with Adaptive Staging. Rather, with Adaptive Staging, a more deliberate, cautious, incremental (learn-as-you-go) set of intermediate goals is implemented on the way to the final goal of a successful repository.

This milestone of initial waste emplacement is important for the implementer to demonstrate the technical and societal viability of geologic disposal.[15] A successful repository program is one that convinces the technical, regulatory, stakeholder,[16] and policy communities that the repository will be safe enough to close, but that

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[13]Adequate funding arrangements are obviously important throughout a repository program. Given the unusually long time frame of the operational phase of the repository (perhaps 50 to 300 years) intergenerational responsibility requires particular emphasis on assuring that adequate funding arrangements are in place for future generations to complete repository operations.

[14]Procedures for closing and sealing the repository include additional measures, such as providing longer-term accessibility of records relevant to the site.

[15]Of course, all decisions about waste emplacement, including achieving the milestone of first waste emplacement, take into account considerations such as long-term containment and stewardship in the indefinite future.

[16]The generic definition of stakeholder used in this report is in Sidebar 3.2 and a specific definition for the United States is in Sidebar 5.2.

arrangements have been made to monitor and continue to evaluate its safety over long time periods.

Although ultimate success will be known only in the far future, one can identify a number of requisites for the successful development of a repository program:

- recognition of future generations' right to a safe and affordable nuclear waste disposal route;
- sufficient consensus on program goals (e.g., safety, cost-effectiveness, and societal acceptability);
- formulation of a reference framework for final disposal, with alternatives, and with the possibility to reverse the course of actions at any point in time;
- recognition that protecting public and worker health and safety at all times is the highest goal, taking precedence over minimizing the time or the costs for implementing disposal projects for radioactive wastes;
- deliberate incorporation of technical and societal input (including input provided by stakeholders) into the stages of the reference framework to maximize safety, cost-effectiveness, and acceptability;
- recognition of the need for regular examination and periodic revisions of the safety aspects of the repository system and of its underlying assumptions;
- recognition of the possibility that the reference framework may evolve using knowledge gained along the way;
- formulation within the reference framework of processes for implementing such potential changes;
- recognition of change as a positive experience and an opportunity to optimize the system, and
- acceptance of responsibility for and timely implementation of key decisions based on assuring safety at all times.

Adopting such a framework does not preclude the disposition of waste in a timely fashion. It does, however, place primary emphasis on the sequential and deliberate development of confidence in repository operations and ultimate performance, with emplacement consistent with such a staged approach.

2

Staged Approaches to Project Development

Early in the study the committee realized that the words "staged," "staging," and similar terms, such as "stepwise," "modular," and "phased," have all been used to describe various aspects of multistep approaches for the development of geologic repositories. However, they evoke different concepts to different readers and may not be synonymous, although these terms are all used to signify some type of iterative approach. In this chapter the committee clarifies its meaning of "adaptive" and "staged approaches" to project development and uses the term "phases" and "stages" to refer to segments of a staged approach (see Appendix G).

The term "Adaptive" as applied to program management has a long history.[1] Holling associated "Adaptive" with "management" in his 1978 book *Adaptive Environmental Assessment and Management.* Holling observed, "Adaptive management is not really much more than common sense" (Holling, 1978, p. 136). The committee subscribes to this view and uses some of Holling's basic ideas for its application to staging.

The committee uses the term "Adaptive" and contrasts it with the term "Linear." Adaptive Staging is not presented as a radical departure from existing methods for managing disposal programs. Rather, Adaptive Staging includes the acknowledged attributes of any system of prudent project management and attempts to put these attributes into an enlarged, consistent framework suited to complex projects that must address or entail significant uncertainties.

2.1 Different types of approaches to staging: Linear and Adaptive

Every large, long-term, and complex project develops in stages. However nuclear waste has unique features that require refinements to more typical applications of staged projects. The refinement begins with the differentiation between two approaches to staging: one is called Linear and the other Adaptive. Both approaches are characterized by stages where the process is divided into smaller units. Linear and Adaptive approaches can be present simultaneously. For example, in an Adaptively Staged project some small tasks can be carried out Linearly. Conversely, unexpected developments (e.g., surprises in the repository geology) can force any project to adapt in ways not considered at the outset of a Linearly Staged project, but that are allowed for in an Adaptively Staged project.

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[1]For further information on adaptation in program management and organizational learning see Aryris (1982); for a recent description of adaptive management see Lee (1993, 1999) and Foundations of Success (2002).

2.1.1 Linear Staging

Linear Staging is defined as a management process characterized by a single predetermined path to a selected, completely defined end point, with stages defined principally as milestones where program progress, costs, and schedules are reviewed. The path and end points are reevaluated only if compelling new evidence or other circumstances absolutely require it. That is, Linear Staging attempts to preserve the specified end point and the path to reach it.

2.1.2 Adaptive Staging

The committee applies the term "Adaptive Staging" to a process divided into phases (see Section 1.2), stages, and Decision Points[2] (see Figures 2.1a, b, and c). The overarching goal of Adaptive Staging is to improve the chances of reaching repository program's success, as defined in Section 1.2.2. The program begins with a reference framework that can be modified, if necessary, by new information.[3] Decision Points mark the transition between stages of project implementation At these points, the implementer evaluates results obtained and information acquired and decides on the optimal path to proceed (see Section 2.4). Subsequent stages are predicated on the outcomes of previous stages. No single path is therefore recognized from the outset as being fixed, flexibility, which allows adaptation of the approach toward agreed overarching goals, is maintained throughout.

This approach emphasizes continuous learning throughout program development: integration of new knowledge is anticipated in the program. Similarly, Decision Points allow the project to adapt and incorporate new information throughout the process. Stages are defined to pursue continuous program improvement until success is reached. Examples of criteria for program improvements may involve increasing safety, cost-effectiveness,[4] or societal acceptance of the repository.

The committee's terminology does not imply that Adaptive Staging and Linear Staging are new concepts, or denies that both approaches have common features, or that there may be a continuum between approaches.[5]

2.2 The safety case at the heart of Adaptive Staging

For radioactive waste repositories, safety is the overriding concern in all program-

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[2]The committee coined the term "Decision Point" and defines it in Section 2.4

[3]The specific path to achieve disposal of high-level waste in a geologic repository is not specified at the outset. At the beginning of any long-term, complex project, the details of the path to the final end point are not clear. Consequently, good cost estimates are also lacking. As the implementer advances in the process, details of the reference framework and cost estimates become better established.

[4]Commitment to systematic learning and cost-effectiveness may appear, at first, to be incompatible. However, cost-effectiveness implies that Adaptive Staging can help avoid the cost of not gathering information and making unwise decisions.

[5]In this report, Adaptive Staging is only briefly juxtaposed to Linear Staging to illustrate the differences between the two approaches. The committee mainly focuses on features, implementation, and impacts of Adaptive Staging

matic decisions. This is sometimes referred to as "safety culture," which means integrating safety into all practices, procedures, and management choices. A key part of the safety culture in geologic repository programs is the "safety case," used in this report as a management tool to guide the implementer's actions during repository development and to communicate the understanding of safety to a broader audience. The committee employs the term safety case in accordance with growing international practice to mean the integrated collection of arguments that support the safety of the repository system (see Sidebar 2.1). The implementer is responsible for development of the safety case even if it is not part of the requirements for the license application (see Sidebar 5.1).

Important features of the safety case are: (1) it contains a understandable (to non-experts) explanation of how safety is achieved; (2) it describes the assumptions and concepts that underlie the performance assessment; (3) it discusses directly the uncertainties that could result from limitations in the scientific understanding of the processes and events determining safety; and (4) it can use other non-quantitative arguments (such as comparisons with independent lines of evidence, such as historical or natural analogues) to support the plausibility of the safety-relevant behavior of the repository system or its individual components. Two primary roles of the safety case are: (1) to guide the work of the implementer while adapting the program at each stage, and (2) to provide the implementer with a vehicle for making the safety arguments understandable by a wide audience. Reassessing the safety case at given stages of repository development provides opportunities to:

- prevent a scenario in which an accumulation of apparently harmless small decisions leads the program onto an unsafe path;
- ensure that the robustness of the system concept allows proposed adaptations to be carried out without unacceptable impacts upon safety;
- check the adequacy of the safety strategy to deal with unresolved, safety-related issues, which are a source for public concerns;
- incorporate new knowledge on the features and processes that determine repository safety performance;
- satisfy the demands for social review, which can potentially increase confidence; and
- take into account any significant change in system requirements, such as the introduction of new waste types to the inventory of waste to be disposed of in the repository.

Demonstrable safety is the prime objective of geologic disposal. Accordingly, during the structured decision-making process between stages, the program implementer conducts a systematic reevaluation of the safety case in view of new information gained during the previous stage and modifies the program, if necessary. The committee does not imply that the safety case is a requirement for a license application or that it is the only way to demonstrate safety. Reevaluation of the safety case does not necessarily involve a re-calculation of numerical results of a safety analysis at the end of each stage, but instead involves a re-assessment of the level of confidence in the understanding of the behavior of all, or part of, the safety barrier system.

SIDEBAR 2.1 The Safety Case as Defined by the Nuclear Energy Agency

Although there is no universally accepted, comprehensive definition of a safety case, various aspects are presented in the Nuclear Energy Agency (NEA, 1999a) report *Confidence in the Long-Term Safety of Deep Geological Repositories*. Relevant sections are reproduced below:

> "The safety case involves descriptions of the possible geological evolutions of the system. Although not capable of proof in a rigorous sense, these descriptions can be supported by relevant observations of the behavior of the various components of the system, while relying on an understanding of its geological history. Furthermore, flexibility should be built into the process of repository development, allowing account to be taken of new understanding and technical information, as well as the demands of societal review.
>
> The safety case that is provided at a particular stage in the planning, construction, operation or closure of a deep geological repository is a part of a broader decision basis that guides the repository-development process. ...
>
> The safety case should make explicit the principles adopted, and methods followed, in order to establish confidence. The approaches to establish confidence in the evaluation of safety should aim to ensure that the decisions taken within the incremental process of repository development are well-founded. ... The key messages [of the report] are highlighted below.
>
> - A safety case should make explicit the approaches that are implemented in order to establish confidence in the safety indicated by an assessment.
> - The assessment basis ... is a key element of any safety case. In order to establish confidence in the safety indicated by an assessment, confidence in the elements of the assessment basis must be evaluated. If necessary, the elements must be modified with a view to achieving confidence enhancement.
> - Confidence evaluation and enhancement are performed iteratively in the preparation of a safety case.
> - Methods exist to evaluate confidence in the safety [of the repository] indicated by an assessment in the inevitable presence of uncertainty. In many cases, it can be determined whether safety is compromised by specific uncertainties through a sensitivity analysis, in which the consequences of such uncertainties are evaluated.
> - Confidence in the safety indicated by an assessment can be enhanced, by ensuring the robustness of the system concept, the quality of the assessment capability, the reliability of its application in performance assessment and the adequacy of the safety strategy to deal with unresolved, safety-relevant issues.

• Observations of natural systems play an important role in the qualitative evaluation and enhancement of confidence, because such systems have evolved over extremely long time-scales.

A statement of confidence in the overall safety indicated by the performance-assessment results is part of the safety case and should include an evaluation of the arguments that were developed, in relation to the decision to be taken" (NEA, 1999a, pp. 9–10).

Sidebar 5.1 discusses the safety case in the U.S. regulatory context.

2.3 Attributes of Adaptive Staging

A successful geologic repository program requires commitment to systematic learning, flexibility, reversibility, transparency, auditability, integrity, and responsiveness. These are the attributes that the committee uses to define Adaptive Staging. Although these attributes may exist separately in any staged project, successful application of Adaptive Staging requires that they be simultaneously satisfied both throughout each stage and in the decision-making process between stages.

- **Commitment to systematic learning.** Commitment to systematic learning requires a structured program aimed at the acquisition and incorporation of new knowledge during the development of geologic repositories. Stages are designed specifically to increase the body of available knowledge, including scientific, technical, societal, institutional, and operational knowledge. Needs and questions are made as explicit as feasible at the outset of each stage. A central feature of Adaptive Staging is that it intentionally seeks, is open to, and learns from stakeholder input in all knowledge areas. The commitment to systematic learning is explicit in both the Adaptive Staging perspective and during program design. To realize the opportunities presented by a commitment to learning, it is also essential that appropriate institutional arrangements and attitudes be in place. Unless the scientific and management systems seek out and welcome alternative viewpoints, openly acknowledge errors and uncertainties, and implement negotiating strategies with local hosts and critics, learning will be minimal.
- **Flexibility.** Flexibility is the capability and the willingness to reevaluate earlier decisions and redesign or change course if warranted by new information. Adaptive Staging is an iterative process that involves periodic reevaluation. Earlier decisions are questioned, or program changes are proposed, only if information gathered suggests the need for amending the next stage and thus altering the reference framework. Flexibility includes consideration of available technical and non-technical knowledge to determine the program direction while keeping options open.
- **Reversibility.** Reversibility is the distinct option to abandon an earlier path and reverse the course of action to a previous stage if new information warrant. Because knowledge will accumulate as the project moves through stages, and project choices are made, the likelihood of reversal is expected to decrease as the project develops. Nevertheless, reversal must remain an option until the pro-

ject is completed. A decision to reverse is evaluated with the same rigor as a decision to advance in light of current knowledge. Reversibility requires that fallback positions be incorporated into disposal policies and technical programs.

- **Transparency.** Transparency implies that the decision-making process is well documented (including clear and comprehensive synthesis of the bases for decisions), and available to all stakeholders throughout the program. Policy and technical considerations must be clearly differentiated; for instance, a statement of intent and rationale behind each stage and Decision Point must be developed and tested for understandability and then broadly publicized to stakeholders. To improve transparency (and auditability) it is also valuable to ensure that key information is not buried indistinguishably in a surfeit of less relevant information. Transparency creates the basis for a dialogue among the implementer, the regulator, external review bodies, and stakeholders.
- **Auditability.** Auditability requires complete documentation of the preceding dialogue and of the basis for decisions The implementer ensures that all documents are readily available to all interested parties, and can be easily obtained and understood. While transparency refers to accessibility of the decision process in more or less real time, auditability refers to accessibility after a decision is made (e.g., for purposes of review).
- **Integrity.** Integrity implies honesty. It means saying what you will do and doing what you say you will do. All uncertainties, assumptions, and indeterminacies are identified and labeled as such. Technical results are accurately and objectively reported and placed in context at each stage. Data applicability and limitations remain openly acknowledged. All relevant results, including those offered by external parties, are also incorporated in the decision-making process.
- **Responsiveness.** Responsiveness requires the implementer to seek, acknowledge, and act on new information and on input from other stakeholders in a timely fashion. Schedules should be planned to allow timely integration of new knowledge into decision-making and includes time to implement changes responding to newly acquired information. To integrate lessons learned from prior stages, planning and evaluation periods are integral parts of an Adaptively Staging's schedule. The committee calls these evaluation periods Decision Points (see Section 2.4).

Taken separately, these attributes do not constitute the process that the committee calls Adaptive Staging. Only the simultaneous presence of these attributes makes the staging process truly Adaptive.[6] They must all be satisfied to ensure proper functioning of the stages and the decision-making process between stages.

[6]The reader should not infer from this report that Linear Staging, by default, lacks all attributes of Adaptive Staging. A key difference between the two approaches is that Adaptive Staging is designed to fulfill all of these attributes, whereas it is not necessarily the case with Linear Staging

2.4 The decision-making process

A structured decision process is an essential part of Adaptive Staging. The purpose of a Decision Point is to assimilate new information, generate options (both anticipated and unanticipated), and make choices for subsequent actions based on acquired data. At Decision Points the implementer, following stakeholder consultation, determines whether the program will proceed or reiterate a previous stage. Decision Points should be planned at the end of all stages to assess the lessons learned. They can also be introduced in a stage whenever necessary (i.e., if new information warrant reconsideration of program direction). The decision to apply for a license (construct, operate, close the repository, or terminate activities) is an example of a planned Decision Point. The decision in the U.S. program to add the titanium drip shield to the engineered barrier system at Yucca Mountain would have been an example of an unplanned Decision Point if it had been carried out as described in this section. The implementer, DOE, judged that the drip shield was required to meet repository performance goals. In contrast with Adaptive Staging, Linear Staging attempts to anticipate all options initially, chooses a path, and does not allow for generating additional options during the process unless an unexpected event forces it. Decision Points in Adaptive Staging add flexibility and opportunities for program improvement with respect to safety, costs, and schedule.

A Decision Point is not just a "point" in time but a process involving analyses, review, and evaluations, as well as the consequent decisions for future actions. Thus, at a Decision Point the program implementer initiates a process that:

1. systematically gathers, synthesizes, evaluates, and applies the information acquired to date;
2. develops options for the next stage, including explicit consideration of reverting to an earlier stage;[7]
3. evaluates and updates the assessment of the safety of the repository system, in light of the options;
4. makes the findings publicly transparent and available;
5. engages in dialogue with stakeholders;
6. decides on the next stage based on all of the above; and
7. disseminates decisions and their rationales.

Figures 2.1a, b, and c illustrate schematically the committee's view of the overall Adaptive Staging process, stages, and Decision Points. The more important or far-reaching the decision, the more it resembles the Decision Point-process above. Of course, the program implementer makes many more decisions than those at the formal Decision Points.

[7]Because reversibility is always an option, it is important that the repository program provide flexibility in its reference framework.

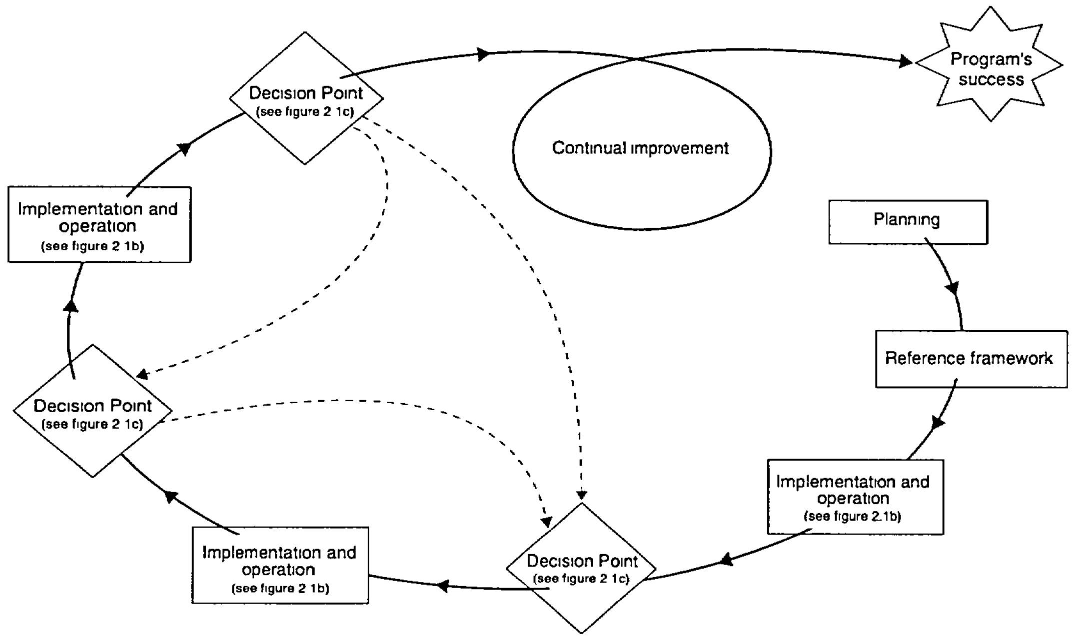

FIGURE 2.1a The Adaptive Staging process. Solid lines display a forward path throughout the repository phases listed in Section 1.2.1. At each Decision Point, the options are shown: to move forward as planned (solid line) or to revisit decisions or work performed in previous stages (dotted lines). The option to revisit a decision can apply to any of the previous Decision Points. Continual improvement indicates progression through stages and Decision Points until achieving program success, as defined in Section 1.2.2. Details of implementation and operational stages and Decision Points are described in Figure 2.1b and c, respectively.

That is the main reason for introducing these comprehensive formal Decision Points throughout the program, i.e., to ensure that a series of relatively small decisions, each made on narrow grounds, do not lead the program onto an unsound path. During the operational phase the implementer is likely to undergo many subsidiary decision processes—both nested and parallel—in various parts of the program, which are in effect overseen and reviewed at the Decision Points. In Adaptive Staging, it is not the frequency of Decision Points that matters; it is the readiness to introduce a Decision Point when it is necessary and to follow the appropriate decision-making process. The transparency attribute of Adaptive Staging allows all parties to ensure that important decisions are treated as Decision Points. Adaptive Staging does not require program "stops" at each Decision Point. Decision Points can be folded into the schedule so that, when a program is proceeding well, no undue delays are required.

Adaptive Staging may appear to be a time-consuming, disruptive, and endless process, particularly because reversibility by definition is an option at every Decision

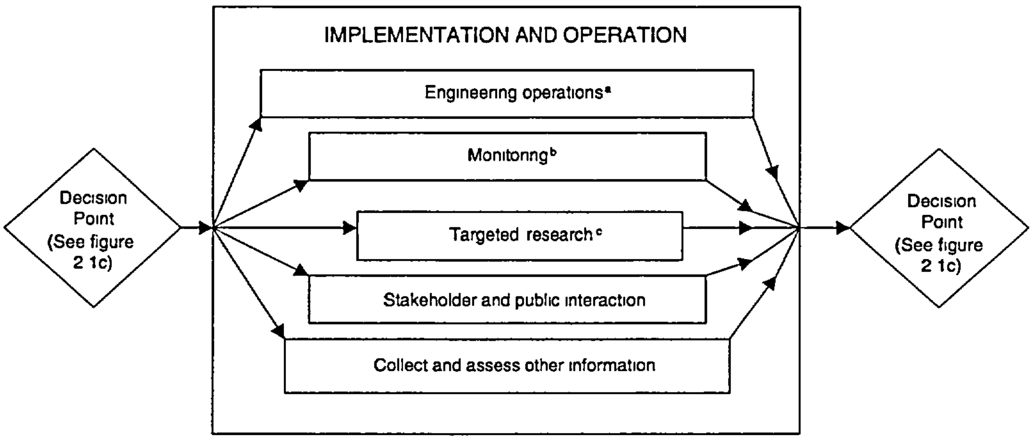

FIGURE 2.1b The Implementation and Operation stage.

[a]Engineering operations can be repository construction, pilot activities, repository operation, closure, etc.

[b]Monitoring implies gathering technical data from the site and from other sources and also societal input (see Section 4.6).

[c]Targeted research includes long-term science and technology program and research in social sciences (see Sections 4. 7 and 4.11, respectively).

Point; however, if questions of safety or planned feasibility do not emerge as the program proceeds, reversal on technical grounds becomes less likely. Similarly, as the program proceeds, choices among alternatives are likely to decline.[8]

Unlike Linear Staging, options remain open for as long as practical when Adaptive Staging is employed. Eventually, Linear and Adaptive approaches converge to an end. If parties involved in the program openly acknowledge that the final path taken may not be the one initially planned, Adaptive Staging has the potential to reduce the perception that changes are a reaction to some failure in the original plan. This perception may be mitigated by using Adaptive Staging when compared to a management approach that sets up and advertises fixed milestones that will inevitably need to be revised with time.

In summary, Adaptive Staging is a cautious and deliberate decision-making and management process, fully consistent with good engineering practices. It emphasizes continuous learning, both technical and societal, includes 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 as much as possible.

[8]Of course, it cannot be excluded that some programs—especially those with active research components using Adaptive Staging—open new options as they proceed.

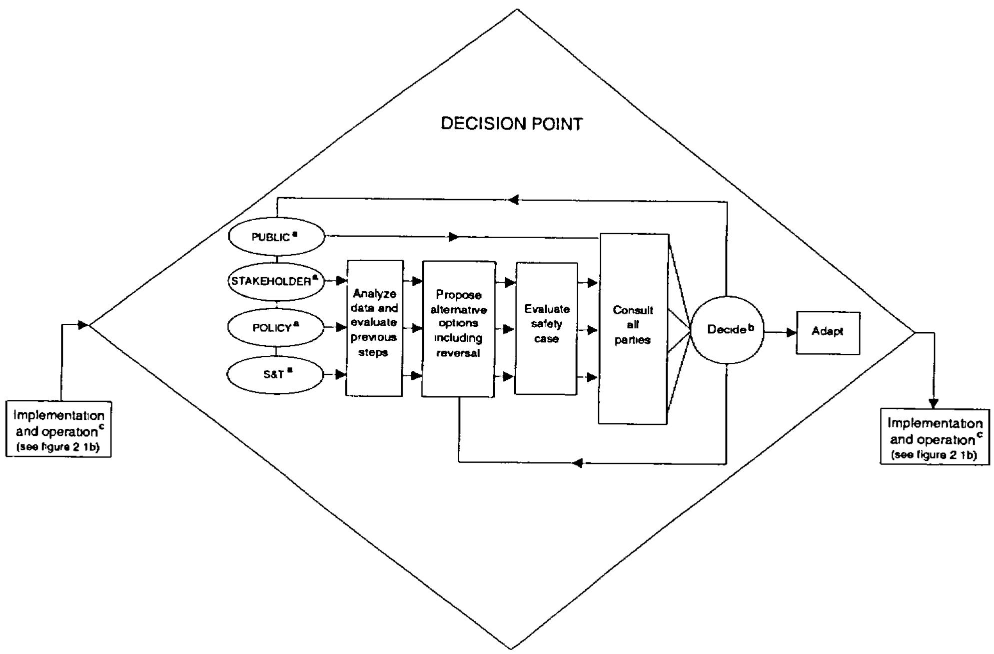

FIGURE 2.1c Decision Point.

[a]Public, stakeholders, policy considerations, and the long-term science and technology program (S&T) provide input for decision-making For a generic definition of stakeholder see Sidebar 3.2.

[b]Responsibility for the decision will depend on the national framework and on the specific issue addressed

[c]Can be an iteration of a previous stage.

2.5 Criteria for Adaptive Staging

Linear Staging is appropriate under certain circumstances; however, in projects facing significant technical uncertainties and societal challenges, an Adaptively Staged approach may offer a greater likelihood of success. The committee has developed project criteria to determine the appropriateness of Adaptive Staging for such projects.[9]

These criteria are interrelated, and they must be assessed simultaneously to determine whether an Adaptively Staged approach has a higher likelihood of success than a Linearly Staged process. The committee presents these criteria as a series of questions. Adaptive Staging may be an appropriate approach to a project when the answer is "yes" to most of the following questions:

[9]These criteria are based on a considerable body of work in organization studies dating back several decades. For further information, see Scott (2003); Thompson (1967); Cyert and March (1963); Lindblom (1965); Steinbrunner (1974); Galbraith (1977); Emery and Trist (1965); Dess and Beard (1984); La Porte (1994, 2000) Similar analyses stem from studies of policy implementation, such as Berman (1980) and Sabatier (1986). For background reading, see Lindblom (1959) and Etzioni (1967)

1. Is the project unprecedented?
2. Is the project goal controversial?
3. Are proposed implementing methods controversial?
4. Are there significant scientific, technical, or non-technical uncertainties?
5. Is the consequence of any implementing action uncertain?
6. Are the project's consequences slow to develop over time (versus immediately apparent)?
7. Are there high real or perceived risks associated with the course of action?
8. Are financial resources limited?
9. Is action required but there is no immediate crisis or emergency?
10. Is there significant societal distrust of implementers, regulators, and other responsible parties?
11. Is the public expecting to participate in decision-making?
12. Are institutional environments turbulent or likely to be modified during the course of the project?

Criterion 1 determines whether there are similar, existing projects from which to gain experience, thus avoiding potential but presently unknown pitfalls. A first-of-a-kind project has a great number of uncertainties and necessitates Adaptive Staging's Decision Points in its stage-by-stage assessment of lessons learned. Answering Questions 2, 3, 4, and 5 in the affirmative means that there is uncertainty about goals, methods, and system properties. Uncertainty in any of these criteria makes Linear planning difficult and likely to fail. Controversy on program goal or implementing methods, Criteria 2 and 3, often accompany value conflicts and other types of social controversies. Adaptive Staging's flexible and reversible approach is both less error-prone (because it operates with more information) and is designed to correct errors quickly, thus allowing forward—but cautious—action in the presence of uncertainty as opposed to "paralysis by analysis."

A "yes" for Criteria 1, 5, and 6 has two meanings: first, confident prediction of outcomes is impossible and second, the environment's response to action is delayed in time. Both of these qualities make Linear Staging likely to fail because a Linear process predicts specific results from specific actions. Adaptive Staging allows management to proceed in smaller steps and to react in almost "real-time" to the outcome of a specific action, whatever the outcome. Linear Staging also lacks reversibility unless it is forced by external events. The implementer may do what is predetermined but later discover unexpected or adverse consequences. With long delays in feedback of results an implementer needs to work within a program that incorporates reversibility into every step—a defining attribute of Adaptive Staging. If Criterion 10 is also affirmed, and the public exhibits distrust in the implementers, delay in feedback becomes a serious impediment to restoring public confidence.

Criterion 7 reflects to some extent the well-known precautionary principle of deferring irreversible actions with potentially large risks. A cautious approach is appropriate if the implementer or regulator judges that there are significant risks associated with any activity. A cautious approach is equally necessary if the public is to be closely involved (as reflected in Criteria 2, 10, and 11), the perception of risk is high, or great potential for hazard prevails.

Limited resources, Criterion 8, can create financial uncertainties that require prudent financial management. Regardless of expectations to the contrary, a complex, first-of-a-kind project cannot be rigidly planned in advance; however, Adaptive Staging provides repeated "assessment" periods, or Decision Points, that can help an implementer avoid expensive wrong decisions or unanticipated blind alleys. However, when resources are limited, the visible and near-term costs of Adaptive Staging[10] are likely to appear significant if they cannot be put into perspective, as is the case with any first-of-a-kind project. Together with Criterion 12, unpredictable changes in the program's policy or regulatory environment mean that tightly structured programs can engender more internal infighting and diminished coordination than a more resilient approach programmed to react to changes at the outset.

If action is needed to manage a situation that does not require a fast response (i.e., it is not an emergency or a crisis) but there are significant uncertainties and potential risks associated with a course of action, a Linear approach is likely to produce failure (Criteria 4, 5, 7, and 9 all answer in the affirmative). A cautious approach focused on learning to reduce the uncertainties, particularly in the short term, is more likely to succeed. However, if the situation (such as a combat threat in a war or an imminent environmental disaster) is deemed to require a fast and substantial (i.e., non-incremental) response, even in the presence of uncertainties and risks, then rather than Adaptive Staging, a "command and control" Linear approach may be appropriate (Criterion 9 is not satisfied). In this stipulated crisis situation, the risk of no action is deemed less desirable than the risk of a wrong action and a "command and control" approach, with all of its attendant risks of choosing an inappropriate strategy and of alienating the public, may be necessary.

Adaptive Staging has built-in transparency. This attribute requires the implementer to make project decisions openly with public participation (Criterion 10). Transparency makes it possible to elicit public input at each Decision Point (Criterion 11) and has the equally important potential benefit of building public trust. Linear Staging, on the other hand, makes most decisions in advance when their rationale and impact may be unclear to the public, stakeholders, and the implementer.

Seemingly innocuous early decisions may commit a Linearly Staged project to a path that later proves inappropriate or even unsafe, undermining public trust and forcing institutional change. But the resilience of Adaptive Staging incorporates possible institutional changes into its planning process (Criterion 12), whereas such changes can derail a Linear process. Moreover, Adaptive Staging could also be vulnerable to disruption. Opposing stakeholders can seek to defeat a project, for instance, by denying resources to assure reversibility and then launching a critique of irretrievable errors.

Linear Staging is occasionally a necessary choice if a real or perceived crisis exists (Criterion 9). Whether a criterion is met will depend on which stakeholder is making the decision and on the national context. For example, answering the question on urgency for action (Criterion 9) is different for various audiences for which the status quo is, or is not, acceptable. Whether Adaptive Staging or Linear Staging is the appropriate strategy does not depend only on Criterion 9 but on the full set of criteria. These issues are illustrated for the specific case of geologic repositories in Section 2.7.

The presence of the above properties for any particular situation is not an "all-or-nothing" matter. Programs are rarely scored all clearly "yes" or clearly "no" for the

[10]Near-term costs of Adaptive Staging include, for example, the costs to ensure reversibility.

above criteria. The challenges are to judge the intensity of each quality and to identify the threshold that indicates that uncertainties are sufficient to forego a Linear process in favor of an Adaptive approach.

Even more challenging is to decide upon a relative weighting for the criteria; this involves subjective judgment and may be dependent on the case being considered. However, in simplified form, if the answer is "no" for most of the questions, a Linear Approach may well be suited to achieving the proposed goals within the assigned schedule and budget. If the answer is "yes" for most of the questions, the committee believes that an Adaptive approach may be a more effective and less error-prone method for managing the project.

Below are two case studies from a technical area other than waste disposal. Each demonstrates the use of these criteria for choosing the most successful management approach. The case studies involve two projects (NASA's Apollo Program and NASA's International Space Station Program) that adopted a management approach similar to Linear Staging. The cases are compared to the criteria given above for Adaptive Staging and discussed in light of their success using a Linearly Staged approach. Discussion of each criterion for both programs is provided in Appendix C. The challenges of NASA's space programs are obviously very different from those of a geologic repository program. Nonetheless, these programs represent first-of-a-kind, complex, and long-term projects that serve to illustrate the application of the criteria defined in this section.

2.5.1 Linear Staging: NASA's Apollo Program

Did this program meet the 12 Adaptive Staging criteria? The "score" is: two criteria for using Adaptive Staging; 10 for not using Adaptive Staging. As shown in Table 2.1, only Criteria 1 and 9 were answered fully in the affirmative: the project was unprecedented and action was required.

The Apollo Program is a successful example of Linear Staging. NASA accomplished what President John F. Kennedy had promised in 1961: to land a man on the Moon within a decade. The program's goal was essentially geopolitical, to demonstrate to the world the prowess of the United States, and this it did, on schedule.

The program received generous financial resources and political support; cost overruns were not a factor in determining success. Supporters could tolerate a few years of overruns; annual program costs peaked two years before the Moon landing, and their decline encouraged continued support (Konkel, 1990). The preceding Mercury and Gemini programs had demonstrated much, if not all, the necessary technology.

Success was a singular event. As soon as the lunar module landed and returned safely to Earth, the Apollo Program was a success by definition. That there were failures cannot be discounted. Three astronauts died in a fire during tests on the ground. Apollo 13 failed to land on the Moon and barely returned to Earth safely. But these failures did not undermine the program's overall success.

2.5.2 Linear Staging: NASA's International Space Station Program

Does this program meet the 12 Adaptive Staging criteria? The "score" is seven criteria for using Adaptive Staging; three for not using Adaptive Staging; and two

TABLE 2.1 Two Case Studies of Linear Approaches in the U.S. Space Program

Criteria for Adaptive Management	APOLLO	ISS
1. Is the project unprecedented?	Yes	Yes
2. Is the project controversial?	No	Yes
3. Are proposed implementing methods controversial?	No	Yes
4. Are there significant scientific, technical, or non-technical uncertainties?	No	No
5. Is the consequence of any implementing action uncertain?	No	Yes
6. Are the project's consequences slow to develop over time (versus immediately apparent)?	No	Yes
7. Are there high real or perceived risks associated with the course of action?	No	No
8. Are financial resources limited?	No	Yes
9. Is action required, but there is no immediate crisis or emergency?	Yes	No
10. Is there significant societal distrust of implementers, regulators, and other responsible parties?	No	Yes & No
11. Is the public expecting to participate in decision-making?	No	Yes & No
12. Are institutional environments turbulent or likely to be modified during the course of the project?	No	Yes

NOTE: Apollo=NASA's Apollo Program; ISS=International Space Station Program. References are in Appendix C.

indeterminate (see Table 2.1). This score suggests that it would have been useful for NASA to move away from a Linear Staging approach. At least in the developmental phase, Linear Staging has not succeeded because of many problems in cost, performance, and schedule.

The program's history bears out the failure of Linear Staging in the development phase. In 1984 NASA promised a large and capable station design for $8 billion within a decade. Eighteen years later development continues and the cost, although still unknown, will be in excess of $40 billion for a much less capable space station. This program is ongoing, so its eventual success is unclear.

2.6 Meeting Adaptive Staging criteria does not guarantee success

Meeting the 12 criteria for Adaptive Staging does not guarantee that this approach will ensure program success. Public trust and confidence in the implementing institutions as well as institutional constancy are important requisites to achieve program goals. These two requisites are discussed next.

2.6.1 Public trust and confidence requirements

When a project lends itself to Adaptive Staging, the ease of applying this flexible approach depends on at least two initial conditions:

1. perceived trustworthiness of implementing institutions, and
2. assurance that current institutions will keep political and economic agreements and maintain continuity for many generations.[11]

The confidence level of stakeholders and the general public (the amount of trust) bears a direct relationship to the degrees of freedom, the amount of resources, and the amount of esteem accorded or withheld from large technical organizations. If there is a surplus of trust in the implementing institutions, their leaders are likely to have a good deal of discretion, sufficient funding to ensure continuity, and considerable esteem and technological autonomy. If the implementing institutions face a deficit of public trust and confidence, conflict is high (even over technical issues), regulatory constraints multiply, resources are difficult to sustain, and consensus becomes increasingly elusive.

The greater the deficit of trust, the more institutional leaders are pressed to recover it. Where there is a great deficit, some argue that recapturing trust may be impossible (Slovic, 1993). Table 2.2 summarizes means for maintaining and enhancing public trust when it has been lost.[12] Reversals of institutional distrust are rare, especially when the institution manages a challenging program. In an environment of distrust and limited institutional constancy, implementing Adaptive Staging will be arduous. Trust is not a pre-requisite for Adaptive Staging. However, some trust is required to begin with this approach, because the end points and routes are not rigorously defined and the decision-making process is of paramount importance to effective implementation.

2.6.2 Institutional constancy requirements

The longer the project, and the more generations of managerial leadership, the greater the likelihood of a loss in institutional memory and commitment. The longer the project, the greater are the risks of trans-generational suspicion and opposition. Therefore, the longer the project, the greater is the need for institutional constancy. Institutional constancy implies organizational perseverance and faithful adherence to the mission and its imperatives over long time periods. The goal of institutional constancy is to give confidence to stakeholders and the general public that organizations will keep to their word from one management generation to another. The characteristics of institutional constancy are listed in Table 2.3 (LaPorte and Keller, 1996).

A deficit of trust and a limited assurance of institutional constancy make implementing any staging program arduous unless institutions and their leaders tackle the deficit. This caveat is especially applicable to Adaptive Staging. Before implementing Adaptive Staging, implementers need an in-depth analysis of existing conditions and in-depth discussions of additional institutional measures.

[11]Absent conditions of trust and confidence, applying a Linear approach may be even harder in the long run than applying an adaptive approach.

[12]For the full development of this argument see La Porte and Metlay (1996) and DOE - SEAB (1993).

TABLE 2.2 Means of Maintaining and Enhancing Trust. Source: Derived from La Porte and Metlay (1996) and DOE (1993).

Interaction with External Parties
• Early, continuous involvement of stakeholders' advisory groups with frequent contact; complete candor, rapid, and full response
• Timely accomplishment of agreements unless modified through an open process established in advance
• Consistent, respectful reaching out to state and community leaders and the general public to inform and consult about technical, operational, societal, and equity aspects of agency activities
• Active, periodic presence of leaders at the highest echelons, visible and accessible to citizens at important agency field sites
• Consistency in approach; willingness to acknowledge mistakes
• Unmistakable local agency and program residential presence that contributes to community affairs and pays through appropriate mechanisms its fair share of the tax and other common burdens
• Assuring negotiated benefits to the community, including resources to the affected host communities, that are needed to detect and respond to unexpected costs
Internal Organizational Conditions
• High professional and managerial competence and discipline in meeting technically realistic schedules with high transparency in the meeting of schedules and goals
• The fostering of a "safety culture"[a] by executives at the highest echelons of participating organizations
• Pursue technical options, the consequences of which are attentive to public concerns and clearly demonstrable to broad segments of the public
• Processes of self-assessment that permit the agency to "get ahead of problems" and openly acknowledge them before they are discovered by outsiders
• Tough internal processes of reviewing and discovering actual operating activities that include stakeholders
• Clear, institutionalized assignment of responsibility for regaining and sustaining public trust and confidence and for ensuring constancy activities

[a]For a definition of safety culture see Section 2.2

The absence of trust is a constraint on any approach, but is perhaps worse for Adaptive Staging because of its emphasis on stakeholder participation. On the other hand, relying on stakeholder participation is what makes Adaptive Staging useful for rebuilding trust.

2.7 Geologic repository programs meet the Adaptive Staging criteria

Geologic repository programs meet all the criteria for Adaptive Staging (Section 2.5).

TABLE 2.3 Characteristics of Institutional Constancy. Source: Derived from La Porte and Keller (1996).

Assurance of Steadfast Political Will
• A culture of commitment with the formal goal of unswerving adherence to the spirit of the initial agreement • Strong articulation of commitments by leaders at the upper echelons of all participating organizations calling on staff to achieve constancy • Clear evidence of organizational continuity with institutional norms that nurture the persistence of commitments across many generations • Vigorous external enforcement from regulatory agencies, stakeholders, and an attentive public
Organizational Infrastructure of Constancy
• Administrative and technical capacity to carry out constancy-assurance activities reinforced by agency rewards[a] • Adequate resources to assure the transfer of requisite technical, cultural, and institutional knowledge from one worker and management generation to another • Analytical and resource support for careful examination of technical changes on future impacts • Capacity to detect and remedy the early onset of likely failure that threatens the future, with the assurance of remediation if failure occurs

[a]In this context, rewards are incentives that go to those who administer "constancy-assurance activities." These would likely be unit supervisors, and professional personnel who build the organizational infrastructure of constancy (i.e., personnel who ensure the requisites mentioned in the bullets above).

- **Criterion 1.** The project of building a geologic repository for high-level waste is first-of-a-kind. Underground waste repositories for other waste types have been implemented (e.g., low-level and intermediate-level waste in Scandinavia and transuranic waste at the Waste Isolation Pilot Plant in the United States) but highly active, long-lived, heat-generating waste has not yet been disposed of permanently.
- **Criterion 2.** The goal of managing high-level waste by geologic isolation as opposed to surface storage is controversial (see Section 1.2.1).
- **Criterion 3.** Examples of controversies about implementation methods are the types of engineered and natural barriers needed, transportation plans, and mechanisms for stakeholder involvement.
- **Criterion 4.** Significant technical and societal uncertainties exist (see Section 1.2.1).
- **Criteria 5 and 6.** The response of the repository environment to action taken is relatively uncertain and develops over time periods that cannot be observed directly by this generation. Recognition of the need to demonstrate retrievability is widespread. Many regulatory programs already require retrievability of the waste from the repository.
- **Criterion 7.** The public fear of nuclear materials, including radioactive waste, has already been discussed. Opinions differ, even within the committee, concerning the risks involved. Some committee members believe that properly sited and designed geologic repositories present limited risks compared with the

and designed geologic repositories present limited risks compared with the many other hazards facing society, in part because almost all analyses of risks from a repository give low or very low estimates. Other members believe that it is difficult or impossible to estimate with adequate accuracy the risk of a geologic repository given the uncertainties. There is agreement, however, that high-level waste (1) presents a very long-term hazard; (2) introduces considerable uncertainties in risk estimates; and (3) potentially affects generations far into the future and it is impossible to say for them what constitutes a "low" risk.

- **Criterion 8.** Financial resources are limited and they may vary in the future, depending on external events, such as national emergencies and political and economic changes.
- **Criterion 9.** Even with increased terrorist activities there is no sense of a short-term emergency or crisis situation with respect to the disposal of spent nuclear fuel and defense-related high-level waste,[13] as opposed to leaving it stored at nuclear power sites or at separate sites. However, the governing institutions in some countries, including the United States, have required action from the implementer.
- **Criterion 10.** According to recent data there has been an overall decline in public trust in institutions (Harris, 1997; Lipset and Schneider, 1987; Pharr and Putnam, 2000). Moreover, the nuclear industry was born with a tradition of secrecy that translated into distrust of nuclear technologies and their implementers.
- **Criterion 11.** The public is concerned about radioactive waste and participates through the administrative rule-making process and its elected representatives in the decision-making process, particularly with respect to siting the repository and establishing transportation routes.
- **Criterion 12.** Given the decades-long time frame for repository development, the implementing institution is likely to undergo several management and institutional changes, and the institution may even disappear. The institutional and societal context of high-level waste repositories is addressed in further detail in Chapter 3.

Judgments differ on criteria. For example, Criterion 9 illustrates the difference concerning real or perceived crisis situations. In most countries the lack of geologic repositories is regarded as an important but not urgent situation. The public, in general, shows limited interest in changing the status quo, namely leaving waste at reactor sites, because there is no evidence that storing commercial spent fuel on the surface is unsafe compared to storage underground or other types of waste disposal (NRC, 2001). Indeed, as is the case in the United States, the public and the decision-makers may become agitated by proposed changes that a repository program brings (e.g., the necessity for finding a site and planning for waste transportation to the site).

This lack of urgency in implementing high-level waste disposal is the case in several national programs and has led to long developmental time scales (e.g., in Switzerland and Japan) or even to postponement of the problem (e.g., in Spain, the United Kingdom, and Canada). In the United States, on the other hand, there are

[13] While there may not be the perception of a short-term emergency or crisis for the disposal of these materials, there is a sense of urgency to manage them.

legal, political, and financial reasons for resolving the challenge of high-level waste disposal with some urgency (see Chapter 5).

With due regard to country-specific differences, the committee believes geologic repository programs fulfill the criteria for Adaptive Staging, implying that Linear approaches are likely to encounter significant obstacles, as has been demonstrated by examples in various radioactive waste management programs.

2.8 Staging in non-U.S. national repository programs

There is a growing international consensus that repository programs have a higher chance of success when they proceed in stages (EDRAM, 2002; NEA, 1996b, 1999a, 2001). The setbacks, controversy, and loss of trust in several national programs have led observers to believe that a staged approach might provide a more resilient structure for the development of repository programs. An awareness of the potential advantages of staging has arisen, in large part, because of the setbacks of various national programs when they try to proceed without sufficient intermediate check points (i.e., when their staged approach was more Linear than Adaptive). Appendix D provides examples of blockages in disposal programs and the attempts made to consider whether applying the attributes of Adaptive Staging may have led to more success.

In recent years setbacks in disposal programs have occurred in the United Kingdom, Germany, Canada, France, and Switzerland. In each of these countries, setbacks lead to the loss of many years of scientific effort and large sums of funding. Disposal programs in other countries have suffered setbacks that are less visible because the programs were less active (Witherspoon and Bodvarsson, 2001). For example, in Spain, the Netherlands, and Argentina, programs have been halted following failures to integrate technical and societal aspects, motivating implementers to seek alternative approaches with higher chances of success. Staging repository programs is one proposed response to the situation, as has been recognized in international groupings (EDRAM, 2002; NEA, 1999b).

Not all programs have been beset by major problems. The most successful spent fuel management programs today are in Finland and Sweden, where complete programs have been developed (Lundqvist, 2001; Vira, 2001a,b), for lengthy interim storage, followed by encapsulation of waste in copper containers, and disposal in crystalline bedrock surrounded by a bentonite backfill. Both of these successful programs followed a staged site-selection process, used underground rock laboratories as places for learning, and emphasized continued direct contacts among personnel of the implementers, regulatory staff, and the public. In Sweden the process included the rejection of two of the proposed sites by local communities in consultative referenda. The Swedish implementer, Svensk Karnbranslehantering (SKB), acknowledged these results and abandoned further study of these sites.

A caveat must be added: both countries have significantly different political systems, different national cultures, and importantly, populations sufficiently small so that maintaining contacts between implementers and stakeholders is a simpler task. Although Adaptive Staging is a helpful approach, it is recognized that there are broader, largely political factors that must also be taken into account.

In summary, even when the attributes are satisfied, use of the relatively untried Adaptive Staging process will not guarantee success. Worldwide experience to date has shown that past approaches to managing disposal programs have met with serious obstacles. Adaptive Staging is a more promising management approach because it addresses many of the challenges facing high-level waste geologic repository programs, as discussed specifically in Chapter 4. Given the long time scales inherent in implementing any geologic repository program and the inherently difficult social challenges, the risk that trying an Adaptive Staging approach might lead to major delays or new problems seems small compared to the potential benefits (i.e., a successful repository program) Ultimately, it is the implementer's decision whether to try this approach as a possible way to develop a geologic repository.

Finally, Adaptive Staging is a useful tool, but only if used in the correct way. The basic requirements of good science and engineering, technical competence of both the implementer and the regulator, as well as transparency, stakeholder participation, and integrity are important regardless of the management approach. Adaptive Staging can help but does not replace these requirements.

3

A Typical Geologic Repository Program

This chapter provides information on the activities that must be planned and executed to implement a geologic repository program. Section 3.1 describes decisions to be made and the activities to be carried out at each stage in a typical repository program.[1] The technical context of repository development enables deliberate learning through Adaptive Staging. However, a geologic repository program unfolds within equally important institutional and societal contexts, which are discussed in Section 3.2. Adaptive Staging can be instrumental in developing a repository that focuses simultaneously on the technical, societal, and institutional challenges. This section is meant to be descriptive, not prescriptive; any specific repository could have more, different, or fewer stages, depending on its circumstances.

3.1 Technical context

The objective of a geologic repository program is to dispose safely of high-level waste deep below the Earth's surface to isolate it from humans and the accessible environment (the biosphere). A geologic repository program is usually composed of the following phases[2]: (1) selection of geologic disposal option(s); (2) selection and characterization of a site or sites; (3) licensing; (4) construction; (5) operation; (6) closure; and (7) post-closure. The statement of task directs the committee to address the operational phases of a repository program, which is interpreted here to mean all phases after the site has been selected (Phases 3 through 7). For completeness the committee also briefly addresses the selection of a geologic disposal option and of a site (Phases 1 and 2).

3.1.1 Phase 1: Selection of geologic disposal option(s)

Basic confidence in a waste disposal program is based on the findings from the early phases. Selection of an underground disposal option involves choosing the types of natural safety barriers (determined by the host rock type and its geologic setting) and engineered safety barriers (e.g., waste matrix and containers and backfill materials) that are best suited to achieving long-term (i.e., tens of thousands of years) isolation of the wastes. Examples of proposed natural barriers are: rock

[1]The U.S. repository program is discussed in Chapter 5.
[2] Phases are defined as main elements of a generic repository program. Phases can be divided into stages (see the glossary, Appendix G).

types such as clay, salt, granite, and tuff; examples of proposed engineered barriers are: glass matrix of reprocessed wastes, the uranium dioxide matrix of spent fuel, fuel cladding, waste canisters, backfills, and drip shields.

In Belgium, Canada, Finland, Sweden, and Switzerland the implementer has made a generic safety case (see Sidebar 2.1) after the selection of an underground geologic disposal option. (This safety case is not required in all countries. For instance, in the United States, the regulations require a safety analysis, which is technically equivalent to a safety case.[3]) The implementer can use data available in the literature or acquire data from geologic sites to support the safety case.

3.1.2 Phase 2: Site selection and characterization

The International Atomic Energy Agency (IAEA) identifies four stages in a "top-down" site selection and characterization process that is purely technical: (1) conception and planning; (2) area survey; (3) site characterization; and (4) site confirmation (IAEA, 1994). These are subdivided below based on the necessity and timeliness of decisions.

3.1.2.1 Conceptual and planning stage

This stage establishes screening guidelines, key deadlines, funding, resources, safety assessment, and regulatory constraints. Screening guidelines factor in natural performance criteria as well as socioeconomic, political, and environmental considerations.

3.1.2.2 Area survey

This stage focuses on finding suitable sites, using the previously developed screening guidelines, based on regional data obtained for sites of interest. Often major areas of a country are screened and a number of potential sites are identified. In a second round of screening the number of sites is narrowed. Only existing data are used, such as data available in the literature or existing laws and regulations. The number of sites selected for preliminary site investigation varies widely.

3.1.2.3 Site characterization

During site characterization the implementer investigates one or more sites to determine suitability with respect to safety and other screening criteria. Preliminary site investigations, including deep drilling or excavations, produce underground geologic data at the candidate site(s). Suitable sites are then subjected to detailed safety assessments, which may be reviewed by regulatory agencies. The implementer uses the newly acquired information to update the site-specific safety report and to apply for a permit for underground exploration by means of shafts or ramps connected to tunnels. Typically the site investigation lasts for several years, but in some cases it has extended over a much longer time period (e.g., two decades for the U.S. Yucca Mountain Project).

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[3]If not specified otherwise, in this report the term safety case refers to either the safety case, as used in an international context, or to the technically-equivalent safety analysis, as used in the U.S. context (the safety case in the United States is discussed in Sidebar 5.1).

The conditions for beginning surface and underground explorations vary among countries. In some countries (e.g., Switzerland) hazardous and radioactive-waste-related laws require a permit, whereas in others (e.g., Germany) mining laws regulate permits. Underground explorations at a potential repository site are occasionally described as "underground laboratories of the second generation" to distinguish them from underground research laboratories, which are developed at sites not intended as repository candidates.

The number of sites selected for confirmation through underground exploration varies. In the early 1980s the United States selected three sites for underground examination: Deaf Smith County, Texas; Hanford, Washington; and Yucca Mountain, Nevada. Sweden designated two sites to be investigated and Finland three. Subsequently, both the United States and Finland decided to concentrate resources on underground exploration of single sites; Sweden still intends to perform underground characterization at two sites.

In France, the current plan is to build two underground laboratories at potential sites in different types of host rocks, although problems are being encountered in the search for a second site in crystalline materials following the agreement with the Bure region to host an underground lab in clay. In Germany, the Gorleben site was originally nominated as the single site to be characterized from underground to judge its potential suitability for hosting a high-level waste repository. The rapid and nontransparent narrowing to this single site has been criticized because the public was not involved in the decision (Witherspoon and Bodvarsson, 2001). The latest siting efforts proposed in Germany during the search for alternatives strongly emphasize a transparent staged process, keeping more than one option open right through to the stage of underground exploration (AkEnd, 2002).

3.1.2.4 Site confirmation

In this stage, the implementer studies the site in greater detail and gathers additional data to determine its suitability. The implementer confirms the suitability of the site through underground exploration, data collection, and analysis. The underground exploration area is located in close proximity to the proposed repository in the repository horizon. The data gathered are incorporated into the "main" safety report submitted to the regulator as part of the repository construction permit application. This confirmation stage could involve the preparation of environmental impact assessments to justify a license application. During site confirmation the implementer selects a baseline repository design to be submitted for license application. The sequential narrowing of the number of sites until confirmation is intended to increase the probability that the final site will be suitable.

An alternative approach, more societally-based, elicits volunteer sites and examines their potential suitability. This approach to siting has been used in Sweden, France, and Taiwan, and is currently being used in Japan. Asking a community or municipality whether it would be prepared to host a repository (assuming site suitability) and moving directly to characterization is recognized by the International Atomic Energy Agency as a justifiable alternative to the sequential narrowing process, provided the safety requirements are independent of how the site was originally identified (IAEA, 1994).

In its 1994 report, the IAEA also discusses siting guidelines for a geologic repository and the site volunteering process. The IAEA recommends that the approach used to assess safety at different sites be similar regardless of how the site is chosen. The key caveat is that it is neither essential nor possible to locate the best possible site. The ultimate goal is a site (and system) that can be shown with a high level of confidence to offer long-term safety and be acceptable to the host community.

To date (2003), only the United States has progressed to the site confirmation phase through sequential narrowing of the number of potential sites. With the 1987 amendment to the Nuclear Waste Policy Act, the U.S. Congress decided that characterization should proceed at only one site, Yucca Mountain, Nevada. On July 9, 2002, the U.S. Congress confirmed that the Yucca Mountain site is suitable for repository development. The implementer (DOE) is now preparing the license application for Yucca Mountain.

3.1.3 Phase 3: Licensing

Repository licensing is a complex process that lasts throughout the repository program. The regulator has two main roles in this phase: (1) set the health and safety standards for waste disposal and (2) decide whether the repository meets those standards. One or two regulators with unique competences are needed to fulfill this role. The role of the implementer is to select a repository design and to submit a license application demonstrating that the proposed repository is safe and complies with regulatory requirements. This "proof" is not absolute in a mathematical sense; it involves showing with "reasonable confidence" that unacceptable risks can be avoided.

The implementer must first be licensed to construct the repository. Regulators are likely to require (no high-level waste repository to date has been licensed) that a license or a license amendment be obtained at each subsequent phase. The implementer applies for a license to receive and emplace waste, applies for a license to close the repository, and applies for a license to terminate repository activities.

The implementer presents to the regulator a construction license application based on the full-inventory safety case; that is, a safety case for the completed facility and the entire amount of the waste to be emplaced. Generally a repository is not developed, reviewed, and approved for only a fraction of the waste, with the idea of requesting approval for incrementally increasing the amounts of waste in the future. Maintaining a safety case for the entire inventory at all stages assures that the implementer chooses the most effective development approach in gaining knowledge to affirm or redirect the repository design. On the basis of the full-inventory safety case, and if the regulator allows this approach, the implementer can apply for construction authorization for a pilot plant in which a portion of the baseline design and a portion of any alternative designs can be implemented. The implementer generally needs a license to begin receiving waste and to operate the repository, and another to close the repository.

3.1.4 Phase 4: Construction

Construction begins once the regulator grants the construction authorization license. The repository consists of surface and subsurface facilities. The surface facilities serve multiple purposes: receiving transportation vehicles, unloading transportation casks, handling waste containers, and preparing (packaging) waste for disposal. A further purpose of the surface facilities is to serve as buffer storage, i.e., to store the waste temporarily either before its emplacement or after retrieval from underground. The subsurface facility consists of access tunnels and drifts serving as the final disposal area.

The construction of surface and subsurface facilities can be conducted in one continuous operation or can proceed in stages. Construction of adequate surface facilities and initial disposal drifts must be completed before waste emplacement can begin at the repository. This, however, does not imply that the final full-scale facilities above or below ground must be ready before shipments commence; successive parts of each may be constructed in parallel with operation.

The surface facility is built to allow for inventory optimization, accommodating various alternatives for waste aging and blending that influence thermal operating modes. Two of the determining factors in the cost of a surface facility are the thermal constraints imposed by the repository design and the measures taken to manage the thermal load of waste. The thermal operating mode also influences the ratio between the disposal volume and the surface of the repository footprint. The size and capacity of the surface storage facilities depend on emplacement and transportation logistics. Before construction, the implementer determines the transportation plan by deciding on shipment rates and underground emplacement rates and preferred transportation mode (i.e., rail, truck, or ship). The implementer then plans how to incrementally increase shipment rates and phase different transportation modes into operation.

The underground facility can be built in its entirety to follow the same baseline design, or it can be built in modules having different designs and operations. For instance, at the beginning of operations, options for thermal operating modes or distances between emplacement drifts can be tested on a pilot scale in different parts of the repository. The implementer proceeds to the next excavation stage once results from tests determine the best design option.

3.1.5 Phase 5: Operation

Before repository operation, the implementer must obtain a license to receive high-level waste from generator sites (typically nuclear power plants) or from centralized interim storage facilities and to emplace it underground. The operational phase consists of at least four activities: (1) waste receipt; (2) waste handling; (3) waste conditioning;[4] and (4) waste emplacement and possibly waste retrieval (see Figure 3.1).

Waste arrives at the site by rail or truck (or by ship for coastal sites) and undergoes inspection. Waste is then removed from the transportation cask and is packaged for disposal. Waste is temporarily stored on the surface waiting for transfer to the subsurface for final emplacement.

Transportation rates can be coupled with underground emplacement rates, which could reduce surface buffer storage needs. If decoupled, the underground emplacement rate can be independent of the shipment rate but may result in an increase in surface buffer storage requirements.

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[4]Waste conditioning includes activities such as sorting, compacting, and repackaging.

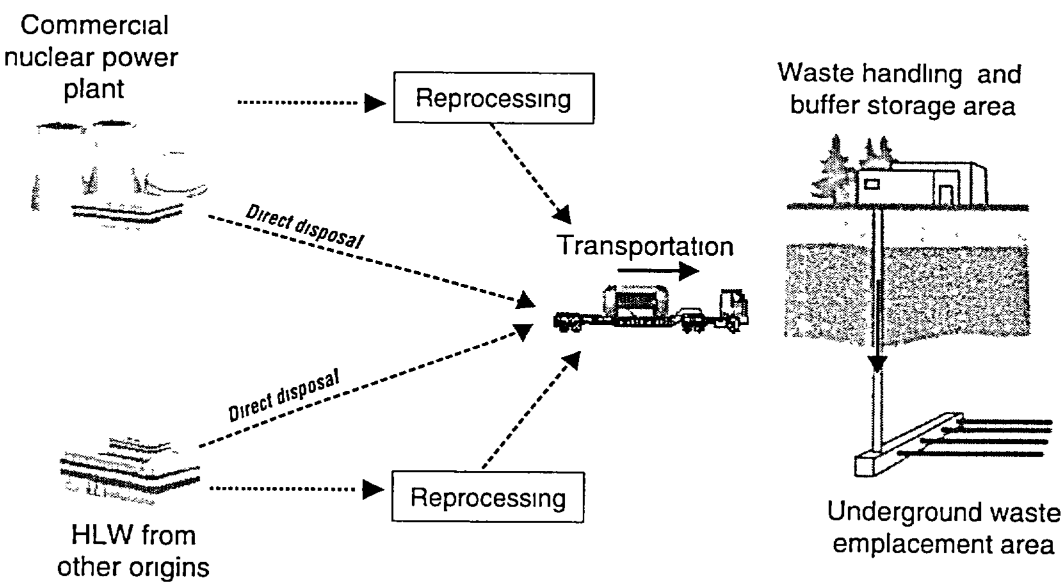

FIGURE 3.1 Geologic repository system during the operational phase. High-level waste (HLW) from commercial nuclear power plants and other origins (e.g., defense activities or research reactors) is either reprocessed and the remaining waste immobilized (e.g., vitrified) before disposal or directly disposed. Waste is transported by rail, truck, or ship to the geologic repository. Waste is received, handled, packaged, and temporarily stored on the surface before final emplacement underground. SOURCE: This figure was adapted from DOE (DOE-OCRWM, 2001b).

During the early operational phase, the implementer demonstrates a capability to take title, transport, receive, handle, package, and emplace waste underground. In many repository programs the implementer is also required to demonstrate retrieval capability, implying the need for at least some planning for substantial surface storage.

The implementer may begin with pilot operations, after which underground emplacement rates are rapidly increased to full-scale implementation. (Some programs, such as that of the United States, intend to increase to full-scale emplacement in a few years) The chosen design may be confirmed in a lengthy demonstration stage.

Some countries, such as Switzerland, propose the implementation of a test facility, which would operate in parallel with the repository, where important, unresolved questions on repository processes could be addressed, unhindered by the demands of waste disposal operations (EKRA, 2000, 2002). Test activities can last for many years or even decades as operations continue. Results from the test facility may lead to adjustments or even significant changes in the repository design or operational strategy if test results reveal significant issues for long-term repository safety. Different pilot operations may be used at different times in the program; for instance, a pilot for a new technology can be introduced during the full-scale operational phase.

3.1.5.1 The pilot stage

The purpose of a pilot stage is to learn about system behavior under the most realistic conditions possible (even if only for a relatively short period of time) and to apply this knowledge to affirm or modify the design and operations. The pilot stage is designed to provide improvement for the engineering and emplacement mode of the waste.[5] In a pilot facility, tests can begin prelicensing with simulated radioactive waste packages and continue with hot radioactive waste packages once a license has been obtained to receive and emplace waste. The introduction of a pilot stage in a repository program is a relatively new idea for repository implementation, although it has already been proposed by SKB in Sweden (Lundqvist, 2001) and has been recommended by the EKRA group in Switzerland (EKRA, 2000). The pilot stage concept is developed in more detail in Chapter 4, Section 4.2.1.

Operations commence with pilot-scale waste handling and emplacement. Information from this pilot is applied to development of the next stage of construction and operation. This stage consists of larger, but still reduced, size or scope modules sufficient to conduct emplacement operations at a magnitude appropriate for evaluation of the issues associated with full-scale throughput. After the pilot stage, the chosen mode of operation for the repository (i.e., radioactive waste receipt, handling, and emplacement) is built up to full-scale operation.

3.1.5.2 Full-scale operations

During full-scale operations, waste emplacement underground is at the fastest scheduled rate. The operational phase ends when all waste has been emplaced underground.

Monitoring activities are an integral portion of operations, as well as throughout the lifetime of the repository program (see Sidebar 3.1). Information derived from monitoring can help the implementation to determine whether the repository is behaving as predicted, and quantitative, reliable information for future decision-making. Current attention in many repository programs is directed toward answering the challenging questions of what and how to monitor in the closure and post-closure phases.

3.1.6 Phase 6: Closure

The implementer applies for a license to close the facility by submitting an updated safety case and an implementation plan for closing and sealing the repository. The closure phase has two main purposes: (1) to monitor the repository before sealing, and (2) to prepare the facility so that the need for future human intervention to maintain safety is minimized.

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[5]The pilot stage also provides the opportunity for the implementer to increase public confidence on the suitability, reversibility, and safety of the repository design.

SIDEBAR 3.1 Monitoring During All Phases

As used here, monitoring applies to the repository and its natural environments. Examples of repository components are: tunnels, waste packages, buffer material, backfills, seals, and monitoring components (e.g., sensors and wiring). Examples of natural environment components are: surface atmosphere, land surface, unsaturated (vadose) zone, saturated zone, and host rocks (near-field and far-field). The International Atomic Energy Agency (IAEA) defines monitoring as continuous or periodic observations and measurements of engineering, environmental, or radiological parameters to help evaluate the behavior of repository system components or the impacts of the repository and its operations on the environment (IAEA, 2001). Monitoring the repository and its environment begins during the site-characterization stage (for baseline studies) and continues through the post-closure phase. Monitoring can continue as long as society believes it is needed and is willing to provide the necessary resources.

The purposes of monitoring are three-fold: (1) to detect any significant change in any property of the repository environment and components (e.g., seismic and volcanic activity) that might increase the probability of a safety failure; (2) to detect an actual failure of a component or a release of radioactive contaminants to the near-field environment; and (3) to detect a process, parameter, or interaction that affects nuclide migration not heretofore recognized. Monitoring data are used to improve repository performance or reduce uncertainties in repository performance. Monitoring information can also be used to improve repository programs in other locations. *(continues on page 53)*

The updated safety case demonstrates that knowledge gained during the operational phase has confirmed expectations or resulted in system adaptations that have reaffirmed confidence in the long-term safety of the repository. If the license for closure is approved, the implementer adapts the monitoring program and proceeds to prepare the repository for sealing and post-closure activities. The closure process itself entails constructing the final engineered barriers, buffers, backfills, and shaft seals for the facility; dismantling surface facilities; and restoring the surface of the site. Closure is considered the final phase of the operational stage. After final construction of engineered barriers, but before deciding whether to approve the sealing of access, a period of monitoring can help assure that at a minimum the seals are effective and stable. The United States has proposed that the monitoring period before sealing the repository last up to 300 years (DOE-OCRWM, 2001b).

Approval for closure implies that waste is not intended to be retrieved for future use or reprocessing and therefore must be safeguarded from external intrusion. Nevertheless, waste retrieval might be attempted after closure. Such circumstances include, for example, a response to a previously undetected flaw in the repository or a future technological breakthrough that makes re-treatment of high-level radioactive wastes viable and desirable. The need for safeguards to maintain security and the desire for continued assurance of safety will influence decisions about post-closure monitoring and about whether to emplace surface markers at, and near, the site to warn future generations of the presence of hazardous radioactive materials

Sidebar 3.1 (cont.)

The first monitoring purpose is important during pre-closure and post-closure, whereas the second purpose becomes more important as waste is emplaced. The third purpose for monitoring is to improve or confirm conceptual models, such as models of infiltration and of the thermo-mechanical behavior of the near-field environment.

Pre-closure monitoring goals include: (1) providing baseline measurements of thermal, chemical, mechanical, geotechnical, and biological conditions before perturbation by the repository system; (2) providing data for analyzing actual system (and component) performance and comparing the data with expectations, including model calculations (compliance); (3) providing data to be used at each stage in decision-making, including improvements in system performance; (4) detecting any system behavior or failures harmful to the environment or human health (compliance); (5) safeguarding nuclear materials; (6) providing data to ensure responsibility and liability; (7) providing information for societal confidence in repository performance; (8) ensuring health of workers during the operational phase of the repository; and (9) complying with existing regulations.

Post-closure monitoring goals also include 2, 4, 5, 6, and 7 above. A widely accepted objective of the international community is that long-term safety of the repository must not rely on institutional controls (i.e., monitoring of the repository) after it has been sealed and closed (IAEA, 2001). However, monitoring after closure can be continued for as long as any institutional control and memory persists to provide input for maintaining confidence in system performance. The conceptual and practical problems in developing a monitoring program are discussed in Appendix E.

in the subsurface. As for any other stage, closure may be performed in a staged manner maintaining reversibility throughout the process.

3.1.7 Phase 7: Post-closure

After site closure, the post-closure monitoring phase begins and can continue indefinitely. When all parties are assured of repository performance and safety, government authorities decide when to cease monitoring activities. Passive institutional controls will be maintained as long as society demands it to minimize the possibility of human intrusion—either intentional or accidental. During the post-closure phase the repository must be safeguarded from external intrusion. The implementer safeguards the repository in two ways: (1) by constructing physical barriers and (2) by engaging in active and passive institutional controls.

Physical barriers may include fences, walls, and other features that inhibit access to the repository. Active institutional control implies the maintenance of measures (e.g., guards) controlling access to the repository area. Passive institutional control implies identifying the controlled area through signs, markers, and monuments, as well as distributing information on the repository and land use to local, regional, and national agencies. During post-closure, responsibility for controlling access to the site may be transferred from the implementer to other appropriate government institutions because of the extremely long periods involved.

Currently, there are no definitive requirements for societal or government activities during the post-closure stage. Because the post-closure phase is so far into the future, it is not possible to predict when, and even if, it will begin. One objective of geologic disposal, however, is that the repository not impose on future generations any obligation for indefinitely long active institutional control (IAEA, 2001). Neither does it preclude it.

3.2 Institutional and societal context

A geologic repository program unfolds in a broad societal and institutional context. This context establishes boundary constraints on decisions concerning the repository and may influence the ultimate success of the program. Some of these issues have been discussed in detail in a previous National Research Council report (NRC, 2001) and by Dunlap et al. (1993), while others, such as institutional challenges for repository implementers, remain to be addressed.[6]

The repository development process must be scientifically and technically sound, but the application of science and technology takes place in a broader context, a context that touches aspects of the larger society in which issues are often framed differently by scientists and technologists. Any successful solution to the disposal of nuclear waste must recognize this broader context. Institutional and societal issues in high-level waste disposal are related to public attitudes toward nuclear power and nuclear waste, public trust in institutions, public acceptance, and stakeholder participation. The committee's definition of stakeholder is given in Sidebar 3.2.

An important basis for the tripartite distinction among different types of stakeholders lies with the respective roles of each. The role of institutional stakeholders is clearly specified in legislative mandates, in rules, and in regulations. Roles of stakeholders and the general public have no similar institutional standing; hence, their roles are specified in this report. The committee underscores the importance of maintaining a clear distinction between stakeholders and the general public, because each serves a distinct, separate role in the Adaptive Staging process.

3.2.1 Public attitudes toward nuclear power and fears about nuclear wastes

A large fraction of the public is unconvinced that benefits of nuclear power outweigh the risks. Nuclear power continues to elicit strong and opposing views among large fractions of the public. The controversy generally includes concerns over safety and waste management (Rosa and Dunlap, 1994; Rosa, 2001). Recently, the events of September 11, 2001, may have heightened public concern over nuclear security.

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[6] In-depth analyses of institutional and societal issues related to geologic disposal of high-level waste are outside the committee's statement of task.

SIDEBAR 3.2 Who is a Stakeholder?

The term "stakeholder" has acquired broad and growing acceptance as the rubric for referring to the wide range of parties who have an interest in a public policy issue. In principle, a stakeholder is any individual, group, or organization that has a legitimate interest, called a "stake," in the outcome of a public policy decision. Hence, a stakeholder, in the context of a nuclear waste repository, potentially includes any person or organization with an interest in, or who is affected by, the decisions of the repository implementer.

Interpreted broadly, a stakeholder can include a wide range of interested parties, from codified institutional entities, such as national legislative bodies, to local communities and local governments, organized public interest groups, and individual citizens. Interpreted narrowly, as is typically the case in practice, a stakeholder is an organized group of activists who have taken an active interest in the repository outcome. Both interpretations have operational disadvantages. The broader interpretation neglects to distinguish stakeholders who have a codified, institutional, and continuous status, such as legislative bodies, the implementer, and the regulators, from individuals and groups whose standing is neither codified nor permanent and whose stake is more issue-specific. It also neglects to distinguish active stakeholders from passive members of the general public. The narrow interpretation ignores the inherent stakeholder status of institutional bodies on the one hand, and leaves out members of the wider public who have a stake in the outcome but remain passive spectators, on the other hand.

To avoid the operational ambiguities in each interpretation the committee distinguishes three categories of stakeholders: institutional stakeholders, stakeholders, and the general public. In this report, institutional stakeholders are identified by their functional role in generic discussions (i.e., as implementers, as regulators, or as other institutional bodies) and by specific titles (i.e., as the Department of Energy, the Nuclear Regulatory Commission, and the Environmental Protection Agency, State of Nevada, and local governments) in connection with their duties associated with the Yucca Mountain repository in the United States. The term "stakeholder" in this report, consistent with typical usage of the term, refers to individuals, groups, and organizations that have an active interest and become engaged in the siting and management of a repository.

The "general public" in this report are all other passive citizens who may have a stake in the siting and management of a repository but remain spectators, unengaged in the decision process.[a]

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[a]A previous National Research Council report (*Understanding Risk*) eschews the term "stakeholder" preferring the term "interested and affected parties." This committee chose the term "stakeholder" because of its widespread familiarity and usage and because it more precisely explicates the institutional status of certain stakeholders and delineates the category of stakeholder participation. Nonetheless, the committee's definition of stakeholder is consistent with that in *Understanding Risk* (NRC, 1996).

Because of the public ambivalence about nuclear power, in general, and the deep dread of nuclear waste, any institution charged with managing its wastes may be tainted from the outset. The general public in almost every nation where data have been collected perceives nuclear technologies and radioactive wastes as the riskiest of all hazards and expresses great concern about them (Cha, 2000; Bastide et al., 1989; Englander et al., 1986; Keown, 1989; Rosa and Machlis, 2002; Slovic, 1987; Teigen et al., 1988). Nuclear fission and its applications, even before their uses could be harnessed and made practical, have been viewed with deep ambivalence and great suspicion (Weart, 1988).

This negative picture is balanced to some extent by considering the current status of nuclear power worldwide. In many ways and in many places, the public implicitly trusts nuclear power technology. Public trust allows over 100 plants in the United States and over 400 worldwide to operate. Recent sales and license extensions suggest that these plants are viewed optimistically for the future.[7] New nuclear power plants are being constructed in the Far East, and Finland has recently decided to construct a new plant. Waste disposal facilities are also accepted by local communities at some locations, as is the case in the United States,[8] Sweden, Finland, France, and Spain. There is, nevertheless, opposition to nuclear power in some countries, such as Sweden, Germany, and Belgium, strong enough for authorities to consider shutting down plants in the future (see Appendix D).

3.2.2 Institutional trust

Levels of public trust have been monitored in the United States in a variety of surveys over the past four decades. Typically respondents are asked to express their level of confidence (trust) in the people running a society's major institutions (e.g., the military, science, medicine, the press, and various branches of government). Since the 1970s, virtually none of these institutions has elicited a majority who say they have great confidence in the people running them.

When citizens are asked about their confidence in the institutions themselves, not in the people running them, a similar pattern emerges. With some exceptions, similar deficits of public confidence in the performance of its institutions are found throughout the European nations and Japan (Pharr and Putnam, 2000).

The failure of most institutions to attract majority confidence represents not a momentary spike of opposition but the manifestation of a pattern that crystallized decades ago and has persisted to the present. Some students of institutional trust (Lipset and Schneider, 1987) have interpreted the data to reveal a three-decade-long downward trend in public confidence, while some polling firms interpret the

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[7]License extensions are multi-million dollar decisions made by organizations (commercial utilities) that are notoriously conservative. Just a few years ago, many were predicting that most plants in the U.S would be shut down when they reached the end of their initial licenses. Utilities' managers would not gamble with license extensions unless they felt strongly that the prospects for re-licensing—and the public support for continued operation of these nuclear plants for 20 more years—were strong.

[8]In the United States the community of Carlsbad, New Mexico, which is hosting the Waste Isolation Pilot Plant, generally enjoys a good relationship with the Department of Energy.

current levels of trust to be the lowest ever recorded (Harris, 1997). The more conservative and defensible interpretation of the data is that there is no evidence whatsoever that institutional trust has increased over the past three and one-half decades and, in fact, trust may have declined somewhat. Either interpretation of the available data—dramatic or slight decline—is troubling to the task of balancing trust between the expert and the layperson. Trust in society's major institutions fails the test of majority support and is clearly far short of being compelling (Rosa and Clark, 1999).

Trust is intertwined with the constancy and continuity expected of institutions charged with managing the operational period of repositories over the time scales of many decades or even hundreds of years. The issue of constancy and continuity is developed more fully in Section 2.6.2 of this report. While there is little question about the connections between trust and constancy, and between trust and continuity, the causes have yet to be established.

It could be the case that a solid base of public trust in implementing and regulatory bodies is a prerequisite to demonstrating their commitment to the constancy and continuity. Or it could be that, where there is a deficit of trust, constancy and continuity are essential prerequisites to re-gaining trust. By this reasoning, the public will only trust institutions that have exhibited competency and fiduciary responsibility over long periods of time. The preponderance of evidence favors this second possibility and, as a consequence, the committee views Adaptive Staging as a promising means for demonstrating the essential prerequisites for regaining trust.

Trust is fundamentally asymmetric in two important ways: (1) trust-decreasing events have greater salience and therefore impact on perceptions than trust-increasing events (Slovic, 1993), and (2) trust is easily and quickly lost, even by a single event, but once lost is typically difficult to regain—if it can be regained at all (Slovic, 1993; Rosa and Clark, 1999). It is unrealistic to expect a rapid turnaround in levels of trust in society's major institutions, and it is even more unrealistic to expect a rapid turnaround in the low levels of trust accorded the U.S. implementer of a waste repository.

Not all repository implementing organizations suffer from such low levels of trust. In Scandinavia the public regards the waste management organizations as the most reliable source of information (Isaacs, 2002). Nevertheless, the findings of the Eurobarometer 2001 confirm the low confidence of the European public in various institutions (INRA, 2002). Regaining lost trust will require an unswerving constancy in addressing public concerns and an extraordinary patience in awaiting positive results. An understanding of the magnitude of the task in building public trust of the implementer can be appreciated by recognizing that public distrust is deep and durable, having been forged by disenfranchisement of public input in the past, as well as by failures of nuclear institutions.

The highest rated trust-increasing event found by Slovic (1993) was a local board that had authority to close a large nuclear power plant in the local community. A key aspect of Finland's 1987 legislation on nuclear waste was the introduction of the "decision-in-principle" concept to the decision-making process with the provision for "the absolute right of veto in the siting process" by candidate communities (Vira, 2001a). This provision, along with the requirement that multiple sites be characterized, was likely a key factor that ensured legitimacy in the process and trust in the implementing bodies; after all, local residents could be confident that they had an absolute veto right and, therefore, a final say in the process. In Sweden, the regulator reviews the waste disposal program every third year and the government takes a decision on whether it complies with legal requirements. Conditions for future work can be issued. This decision-process is comparable to the Finnish "decision-in-principle." A decision by the regulator (supervising authority, government) is a potentially trust-increasing measure because it is a clear sign of engagement, evaluation, and acceptance of the repository program by high-level decision-makers.

Of course, having the above conditions is no guarantee for success. In Switzerland, the Wellenberg site was chosen from multiple possibilities in a process directly approved by bodies including local stakeholders (McKinley et al., 2001). The current law gives the region (canton) the veto rights mentioned. The outcome of the recent referendum, however, was that this veto right was used to prevent further progress (Kowalski, 2002). This veto was at the canton level, with the potential host community voting for the third time in favor of the project. This provides a sobering reminder that political and institutional realities must be balanced against the search for optimal processes leading to societal consensus. This is also a reminder that the community nearest to the repository may be in favor of the project, while communities further afield do not support the repository.[9]

3.2.3 Public acceptance

There is universal agreement that a sufficient level of public acceptance is indispensable to the success of any program to manage high-level nuclear wastes (NEA, 2002), but this agreement raises the first of several challenging issues. It must be noted that it is not possible to characterize public acceptance in general terms: there are many types of public audiences and local representatives do not necessarily share the rationale of the representatives of each state or of the federal government.

There is little agreement over how to define "public acceptance." What are the criteria to judge that a procedure for the management of high-level waste has been deemed acceptable? Unlike elections with "one-person-one-vote," where preferences can be reasonably gauged, in most countries no such formalized procedure or rules for judging preferences exist for deciding nuclear waste issues. In countries where referenda are possible (e.g., Switzerland) the question arises of who is entitled to vote: local, regional, or national populations. There is the possibility of taking the point of view that public acceptance is established when there is little public opposition, either directly or through activist organizations, to policies and procedures or when those who can stop a project choose not to. Yet this position attracts its own share of challenges, such as when to judge that levels of opposition have been validly assessed or how to determine that opposition has permanently subsided. The challenging question remains for society and for the implementer of high-level waste programs: when is public acceptance attained?

More troubling is the possibility that it may be impossible in some countries, at least within the near foreseeable future, to generate sufficiently wide public acceptance—however defined—of a high-level waste repository or any other method of high-level waste disposition. The public in most countries, wary of nuclear technol-

[9]For instance, consider the cases of the communities of Clark and Nye counties in Nevada, with respect to Yucca Mountain and those of Carlsbad and Santa Fe in New Mexico, with respect to the Waste Isolation Pilot Plant (Dunlap et al., 1993; McCutcheon, 2002)

ogy in general, is particularly concerned about the risk of radioactive wastes, has low levels of trust in society's major institutions, and has even lower levels of trust in the implementing bodies. Under such conditions, public acceptance for the foreseeable future may be elusive.

There is growing recognition of the need to more actively engage stakeholders and the general public in making key decisions about nuclear waste management (NEA, 2002). The first law of public involvement could be: ignoring the public in such decisions all but guarantees a policy failure. Engaging stakeholders and the general public does not, however, guarantee success. The implications are:

1. there is a higher probability, but not certainty, of success with stakeholder and general public involvement and, therefore,
2. this is the most prudent path to take in a controversial project, but
3. a myriad of further political, institutional, and technical issues are inextricably entwined with the question of public involvement.

3.2.4 Stakeholder participation

The term "interested and affected party"—introduced in a previous National Research Council report (NRC, 1996) and often used as a broad definition of stakeholder (see Sidebar 3.2)—opens a variety of unresolved operational issues. First among these is the relative standing of the respective stakeholders: (1) Should all who are franchised have equal standing in the decision-making process? (2) If so, by what procedures should preferences inform decisions? For example, should each citizen's views be given the same weight as long-standing institutional parties? Or, how are the value differences that define and separate stakeholder groups to be aggregated? (3) If not all who are franchised have equal standing, by what principles are differential standings accorded to the variety of stakeholders?

A second operational challenge is the decision over the most effective institutional mechanism for facilitating public involvement. This is one of the fastest growing areas in research on risk and public decision-making, but research is still in its experimental stage. A wide and growing variety of mechanisms have been developed and field-tested to engage the public in scientific and technological decision-making, and others are currently under development. Some of the more well-known public involvement mechanisms include citizen juries, electronic democracy, deliberative opinion polls, consensus conferences and other consensus techniques, stakeholder dialogues, and cooperative discourse. A few of these mechanisms are theoretically derived, such as the work of Renn and his colleagues and that of Wene and Espjo, but most are pragmatically derived with a focus on arriving at acceptable policies (Webler et al., 1995; Renn et al., 1995; Wene and Espejo, 1999; Klinke and Renn, 2002).

Typically these mechanisms are applied broadly in science and technology policy (e.g., policies on biotechnology or on genetically modified organisms) or to the siting of local facilities (e.g., non-nuclear power plants), often noxious ones (e.g., landfills and incinerators). There are no examples where the public has been engaged in technological decision-making in a situation similar to the complex development of a geologic repository for radioactive waste.[10] Hence, the potential success of any of these techniques, either alone or in combination, to address high-level waste issues, including the siting of a repository, remains untested.

In many countries, the Environmental Impact Assessment and the Environmental Impact Statement initiate important processes by which stakeholders are formally (and also in reality) engaged and given a specified role. The Environmental Impact Assessment may start at different phases and have a somewhat different application in different countries, but is important in the construction, operational, and in closure phases of a geologic repository.

In principle, any approach to the development of a geologic repository that addresses public concerns and enhances trust in the institutions increases chances of success. Adaptive Staging offers opportunities (see Section 4.11.1) and mechanisms to address societal and institutional challenges

3.3 Adaptive Staging is suitable for the development of a geologic repository

A repository program is a suitable candidate for application of Adaptive Staging. Section 2.7 demonstrated that a repository meets the criteria for Adaptive Staging. Unlike many other high-technology ventures, a repository has inherent characteristics that facilitate the use of a cautious management approach with scope for learning in both technical and societal areas.

The committee believes that Adaptive Staging can lead to a number of important benefits in a repository development program.

- It allows the program to improve performance, both pre- and post-closure (e.g., environmental health and safety, cost, schedule, public, and implementer confidence) by building in an approach that seeks and values improvement based on experience.
- It allows the program to improve confidence by narrowing the uncertainties (although some uncertainty will inevitably remain, and with it residual risks).
- It could improve the level of stakeholder and general public trust in implementers and regulators by enhancing prospects of recognizing either a deficient engineering component or an unsuitable site and by providing the mechanism to accept and respond to that finding (e.g., by adaptation, reversibility, or retrievability).
- It gives the program better opportunities for earning stakeholder and public trust by building in numerous stages where the implementer can demonstrate readiness and ability to fulfill promises, work competently, and respond to stakeholder concerns.
- It transforms the implementation of a repository program from a commitment to emplace waste by a fixed deadline to a more measured approach that has as its prime objective the desire to provide a solution defined by current generations that does not preclude future generations from choosing alternative solutions.

[10]One possible example is the Waste Isolation Pilot Plant, the only licensed deep geologic repository for transuranic waste (which is not high-level waste) in the United States.

To be effective, Adaptive Staging should involve the implementer, the regulator, stakeholders, and the general public. It must be accepted and understood throughout the management system and by all stakeholders in terms that include consideration of technical, societal, political, institutional, as well as regulatory systems. Adoption of Adaptive Staging requires, on the part of all involved parties, a readiness to accept and address uncertainties and to acknowledge that unexpected outcomes and occurrences, which are inevitable, are also learning opportunities to improve the system.

Adaptive Staging can bring significant benefits, in the committee's view, to the extent that it can be implemented credibly by the organizations charged with waste management. A fundamental frailty of waste management programs is the ambivalence of societies to undertake the irreversible steps required for final disposal of wastes, even though safe management is seen as essential everywhere. Adaptive Staging can be a way to build the trust needed to take these irreversible steps, but Adaptive Staging itself requires some trust as a precondition, if the long, slow process of learning is to be permitted to unfold in the face of surprises and changes in the guiding hypotheses (i.e., the safety case).

If Adaptive Staging is effective, program changes are likely to decrease with time, as ways are found by the learning-driven process to make the design more robust within a given budget, or more cost-effective for a given level of technology. That is, Adaptive Staging would be expected to converge to Linear Staging from a technological and natural scientific perspective, assuming a stable social environment. This trajectory will not be followed, of course, if unexpected events continue happening. It may be possible to develop and maintain a technical consensus on the likely performance of the repository system, so that the Adaptive process would, over time, build increasing public confidence in the behavior of the repository geology and engineered barriers.

It seems less likely that the social environment of the program can be similarly well defined. The repository is planned to be open for a time period several times as long as the time that has elapsed since the rise of the environmental movement. The social setting of nuclear energy changed with remarkable speed from postwar optimism to one in which dread became the dominant political and economic factor by the late 1970s. These changes occurred in less time than the economic lifetime of the power plants built for civilian purposes, being among the factors leading in some cases to large-scale stranding of expensive capital assets. The social context is historical; it has been and will continue to be path-dependent, so that both extrapolation from the past and causal predication will be unreliable for some time to come. Adaptive Staging not only affects the geologic repository but also has impacts on the entire radioactive waste management system, as described in the next chapter.

4

Impacts of Adaptive Staging on a Repository Program

The criteria presented in Chapter 2 (Section 2.5) suggest that a geologic repository program could benefit from Adaptive Staging. Previous approaches to repository development, often based on a Linear approach, have met serious obstacles (see Section 2.7). As noted previously, the committee believes that Adaptive Staging is a promising approach that can increase the likelihood of a program's success, as defined in Chapter 1. Adaptive Staging is in important ways unproven, both in the context of complex, first-of-kind projects, and for natural resource programs (in which the concept was initially developed). At the same time, Adaptive Staging is similar to staged development of other complex projects, such as the approval of pharmaceuticals, structural designs, and is parallel in logic to open-source software development. The advantages of learning in all these arenas are apparent.

The difficulty of implementing Adaptive Staging is not that learning makes sense and is advantageous as compared to Linear Staging Instead, what is difficult is assuring that learning can be obtained over long time periods and that learning can be used in implementation, and in the face of organizational and political commitments to a Linear model. In addition, deliberate learning requires greater expense for gathering information; it is unclear, however, whether Linear development of a repository under intense scrutiny and conflict incurs any less costs for information gathering and management.

The statement of task directs the committee to discuss Adaptive Staging in terms of:

- repository program,
- safety,
- security,
- regulatory context, and
- institutional and societal context.

The committee identified below knowledge gaps to consider when adopting Adaptive Staging.

4.1 Knowledge gaps

There are several knowledge gaps that must be considered when judging whether to apply the principles of Adaptive Staging in repository development. These fall into three categories related to· the effectiveness of Adaptive Staging;

implementation procedures; and the behavior of the technical and societal environment.

4.1.1 Effectiveness of Adaptive Staging

Adaptive Staging is an untried approach. The effectiveness of adaptive approaches, as applied to natural resources management, has been evaluated by Lee (1993,1999). Lee examined the conceptual, technical, equity, and practical strengths and limitations of adaptive management and arrived at the following conclusions: (1) adaptive management has been more influential, so far, as an idea than as a practical means of gaining insight into the behavior of ecosystems utilized and inhabited by humans; (2) adaptive management should be used only after disputing parties have agreed to an agenda of questions to be answered using the Adaptive approach (this is not how the approach has been used to date); (3) efficient, effective societal learning of the kind facilitated by adaptive management is likely to be important in managing ecosystems as humanity searches for a sustainable economy (Lee, 1999).

Hence, though promising in principle, Adaptive Staging has yet to be demonstrated. In addition, there are knowledge gaps on technological, organizational, policy, and managerial factors associated with the ultimate effectiveness of Adaptive Staging. Section 2.6.2 addresses institutional requirements for effective implementation of Adaptive Staging. Examples of key questions are:

- What is the initial level of public trust and institutional constancy in the implementer?
- What is the relationship between institutional constancy and public trust?
- What are the institutional requirements for implementation of Adaptive Staging?
- What does the implementer need to do to assure that unnecessary delays do not result from Adaptive Staging?
- What changes does it imply within the culture of the implementer and the regulators?

4.1.2 Implementation procedures

In addition to generic knowledge gaps of any geologic repository development program,[1] there are gaps concerning the implementation of Adaptive Staging, particularly from an institutional perspective. Examples of key questions are shown here:

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[1]Examples of knowledge gaps common to Linear and Adaptive Staging are: (1) Will the technology needed to monitor key parameters of repository behavior be available? (2) How extensive, spatially and temporally, should a monitoring program be? (3) Are mechanisms for effective stakeholder and public participation available?

- How are the criteria for moving to a forward stage or reverting to a previous stage determined?
- How can the implementer and the regulator collaborate to ensure the requisite regulatory flexibility?
- How are costs estimated compared to a Linearly Staged program?
- How are public acceptance and institutional performance monitored?
- How is institutional constancy ensured?
- How can public trust be maintained and enhanced?
- How is transparency maintained over time?
- How might political leaders assure the integrity and constancy of the implementing and regulating institutions?

4.1.3 Behavior of the technical and societal environment

Knowledge gaps in the behavior of the technical environment include unknowns about the behavior of the repository and its surroundings and how changes introduced by Adaptive Staging might affect that system. These gaps might lead the implementer to introduce research programs explicitly aimed at clarifying such issues at various stages of repository planning and implementation.

Knowledge gaps in the behavior of the societal environment include two main issues. First, there is widespread agreement that public acceptance is indispensable to the success of any program to manage high-level nuclear waste, but there is little agreement on how to obtain it. Examples of remaining key questions are:

- What is "public acceptance" or "public support"?
- When is public acceptance attained?
- What is the relative standing of respective stakeholders?
  -Should all who are recognized by the implementer have equal standing in the decision-making process?
  -If so, by what procedures should preferences be aggregated to inform decisions? (For example, should each citizen's views be given the same weight as long-standing institutional actors? Or, how are the value differences that define and separate stakeholder groups to be aggregated?)
  -If not all who are recognized by the definition have equal standing, by what principles are different standings accorded to the variety of stakeholders?

As for the second issue, there have been few geologic repository programs in which stakeholders or the general public have been engaged in technological decision-making.[2] A mechanism for including them in the decision-making process remains untested and thus unknown. However, mechanisms are being debated in many countries (NEA, 2002). In France and England, a neutral institution has been selected or established to act as a mediator between various stakeholders (Depeche Meusienne, 2002; UKCEED, 2000). There is need to investigate organiza-

[2]Although there are instances, e.g., in Finland, where stakeholders have taken part in repository site selection.

tional and social processes important to public trust, institutional constancy, and the sustaining of political support for a decades-long program that will be expensive but virtually invisible unless the program is failing.

The committee had neither the information nor the time to identify all knowledge gaps or to propose approaches to address them. Some of the knowledge gaps related to these issues have been discussed in previous National Research Council reports (NRC, 1996, 2001). None of these uncertainties prevents the implementer from applying Adaptive Staging. The knowledge gaps of the last two categories are present whether the implementer uses Adaptive Staging or Linear Staging. A primary reason for adopting an Adaptive Staging approach is that the implementer facing first-of-a-kind challenges can gain experience and thereby improve its program. A guiding principle of Adaptive Staging is that opportunities should be grasped to implement specific scientific or social science research aimed at filling the knowledge gaps, reducing uncertainties, and improving safety.

4.2 Impact on repository program's phases[3]

Adaptive Staging affects repository operations, costs, schedules, buffer surface storage, waste transportation, monitoring, and the long-term science and technology program. Just as the individual attributes of Adaptive Staging are not unique to this management approach, some of the impacts discussed below can also result when other approaches are employed. Adaptive Staging also raises important issues concerning safety, security, regulatory processes, institutional requirements, and societal interactions. The committee assesses whether this impact is advantageous for geologic repositories. In some cases the impact of Adaptive Staging may be empirically determined through implementation rather than by theoretical studies.

Both Linear and Adaptive Staging begin with a planned a course of action divided into stages. Unlike Linear Staging, Adaptive Staging uses a reference framework that is flexible and incorporates Decision Points between stages (see Section 2.3). Throughout Adaptive Staging and in particular during the consultation and evaluation processes at Decision Points, the implementer incorporates all attributes of Adaptive Staging: commitment to systematic learning, flexibility, reversibility, transparency, auditability, integrity, and responsiveness. New knowledge, continuously incorporated into the program, is used to guide the formulation of a next stage most suited to moving the program toward its goals. Planning also includes defining roles and mechanisms for interested and affected parties (e.g., implementer, regulator, stakeholders, and the general public) involved in the program. From the beginning, these parties must be aware of the definition of program success, acknowledge that there may be a number of unresolved issues at each stage, and recognize that program adjustments may result as knowledge is improved. The roles of implementer and regulator are described throughout this chapter. Possible roles for stakeholders are sketched below.

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[3]The statement of task directs the committee to address operational phases, beginning with licensing. The impact of Adaptive Staging on site characterization and selection are not addressed.

The implementer could work with the affected state(s) and/or with regional or local communities to establish a technical oversight group and a stakeholder advisory board; both groups are independent from the national government. These groups can provide independent technical and non-technical analyses of, and advice on, the repository development program. The technical oversight group and the stakeholder advisory board differ in scope of responsibility and nature of membership.

The stakeholder advisory board could work in an advisory capacity to the implementer and serve as a forum to allow project management to engage in dialogue with members of external communities, to improve mutual understanding, and to promote consensus on issues of concern. The technical oversight board would advise on scientific and technical aspects of the program, such as implementation stages (e.g., repository construction and waste emplacement) and the long-term science and technology program In these roles, both groups would participate as needed in Decision Points. The work of the technical oversight board would, perhaps, overlap to some degree with that done by existing review groups appointed by the national governments (e.g., the Nuclear Waste Technical Review Board in the United States, the Radioactive Waste Management Advisory Committee in the United Kingdom, the National Council for Nuclear Waste in Sweden, and the *Commission Nationale d'Evaluation* in France). However, the independent technical oversight group would focus on local and regional issues and its input would be directly integrated into Decision Points by the implementer.

Membership of the technical oversight group could include independent technical experts in disciplines relevant to repository development, including the social sciences, appointed by and reporting to an entity not directly connected with the program. The identity of this entity would be determined for example, through negotiation with affected local institutional stakeholders and the national government.

On the other hand, stakeholder advisory board would represent stakeholder interests. Membership could include representatives from institutional stakeholders and other stakeholder groups—such as local institutions, local and affected governments, universities, as well as representatives from the industry, non-profit, and labor organizations—with the choice of members being made by these institutions.

As with Linear Staging, the implementer presents to the regulator a reference repository design to obtain construction authorization. With Linear Staging this design is fixed and does not account for the possibility that knowledge gained can change the design (unless an event makes the change unavoidable). With Adaptive Staging there are different possible end points in a reference framework. Parties acknowledge that the design can be changed and optimized as experience is gained. The reference design with Adaptive Staging can include test and pilot facilities where reference and alternative design can be tested. Both Linear and Adaptive Staging reference designs can be changed through license amendments, but under Adaptive Staging the regulator acknowledges the possibility of changing the repository design after the first license is granted. Another difference between Adaptive and Linear Staging is that with Adaptive Staging if flexibility and reversibility are maintained in the reference framework, agreement on goals is sufficient.

In the planning that leads to the reference framework the implementer performs careful analysis of the implications of proposing alternatives (including reversibility) at each Decision Point. There are at least two types of planning involved. The first type concerns programmatic goals; analysis of each alternative is integrated with such considerations as costs, schedules, buffer storage requirements, and transportation plans. The second type addresses the technical and societal environment in which the project must be developed (regulatory constraints and institutional and societal considerations). The committee terms this planning "systemic." Examples of planning activities that the implementer undertakes to establish the reference framework using Adaptive Staging are as follows:

- Programmatic planning
  -Planning stages and Decision Points (with the understanding that they may be changed).
  -Identifying foreseeable alternatives in the reference framework and their implications.
  -Considering reversibility and implications thereof.[4]
  -Planning the licensing strategy.
  -Identifying foreseeable knowledge gaps and learning opportunities.
  -Planning a long-term science and technology program to address technical knowledge gaps.
  -Expanding the monitoring program to assess pre-closure and post-closure performance and to address technical, societal, and institutional knowledge gaps.
  -Integrating the transportation program with the reference framework and its alternatives.
  -Considering the surface storage capability needed to ensure flexibility and reversibility.
  -Planning incorporation of new knowledge from in the program and from outside sources.
- Systemic planning
  -Working out an agreement with the regulator on licensing strategy.
  -Identifying safeguard vulnerabilities.
  -Identifying learning opportunities, including social and institutional sciences.
  -Planning research in social sciences to address societal and institutional knowledge gaps (see Sidebar 4.1).
  -Identifying roles of a stakeholder advisory board and a technical oversight group as well as mechanisms for input in decision-making (see Sidebar 4.2).

Of course, Linear Staging also can involve similar programmatic and system planning. The key difference with Adaptive Staging is that, although the reference framework is the most likely path to program's success, at the outset of the program all parties acknowledge the possibility for changes in light of new knowledge, if warranted.

4.2.1 Impact on licensing, construction, and the early operational phase

Adaptive Staging has impacts on the licensing, construction, and early operational phases through:

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[4]The Nuclear Energy Agency suggests: "Reversibility may be facilitated, for example, by adopting small steps and frequent reviews in the program, as well as by incorporating engineering measures" (NEA, 2001b, p. 11)

Sidebar 4.1. Focused Social Science Research as an Integral Component of Adaptive Staging

The implementation of Adaptive Staging emphasizes continuous, systematic learning in both technical and societal areas. Indeed, key features of Adaptive Staging are its explicit provision for societal and institutional learning, in parallel with scientific and technical learning, and the incorporation of the combined learning into the Decision Points. Consequently, various sections of this report outline a range of societal and institutional issues that need to be addressed to implement Adaptive Staging most effectively Operationally, the inclusion of these societal and institutional issues requires a social science research and development (R & D) effort parallel to the science and engineering R & D.

The social science research program is intended to provide information and analyses on:

1. organizational and operational characteristics of a radioactive waste management program,
2. institutional characteristics that are needed to ensure confident performance for many management generations,
3. institutional and organizational factors affecting cost and risk estimates, and budgetary and regulatory accountability, and
4. processes for public engagement, input, and feedback.

The program comprises study of the following key elements:

Operational characteristics, focusing particularly on the information, data, and other evidence to assess the administrative character of the overall repository system. Specific research tasks include the study of.

- The extent to which high levels of reliability in operations are required throughout the repository system, and the changes in current practices (including the provision for a continuous, committed management structure) needed to develop sustained and safe operations.
- The mechanisms most appropriate for societal monitoring of repository development, performance confirmation, and ensuring the transparency and auditability of repository construction and operations.
- The changes that may be needed in the affected regulatory and oversight communities to accommodate the increased movement of radioactive materials in a long, extended process that will challenge multiple management generations. This would include the potential changes in waste transportation systems and the special accommodations, if any, for current and future vehicles, rail yard master systems, and highway management systems.

Institutional Characteristics, emphasizing the contexts, rules, and practices that determine organizational effectiveness and the significant role played by the external environment in shaping organizational performance. An understanding of these characteristics can be pursued through study of:

- The institutional conditions necessary to sustain trust throughout the decades of repository operations and the centuries following repository closure.
- The incentives and processes needed to assure stakeholders, the implementer, and governmental agencies that contractors and operators will rise to the level of competence and transparency that are needed to gain and maintain trust across the generations inherent in radioactive waste management systems.
- Baseline levels and trends in the external social, cultural, and political environment, such as: the levels of public trust or the activity of social movements, the shared beliefs about technology, or the changing dynamics of geopolitics (e.g., terrorist threats) likely to impact repository construction or operations.

The institutional and organizational factors affecting the basis for costs and risk estimates, and budgetary and regulatory accountability, including the capacity to make reasonable estimates and to take appropriate actions. Specific lines of research include:

- The means to develop a credible data basis for cost estimates (including social costs) and for repository system performance evaluation that take life cycle operations into account.
- The assembly and collection of data and analyses of perceptions of risks and institutional trust, the changes in such perceptions, and the sources of those changes.

Public understanding and engagement, emphasizing a two-way process of communication and transparency to enhance chances of public acceptability. Research could be devoted to the following tasks:

- Determining the relative efficacy of alternative methods for engaging independent bodies and stakeholders to assess the development and operational phases of radioactive waste management programs.
- Identifying the most effective communication mechanisms for the sharing of relevant information among institutional stakeholders, stakeholders, and the public.
- Managing and coordinating the different streams of knowledge and learning—technical, procedural, and social.
- Determining the most effective mechanisms of public engagement, based upon systematic field experiments.
- Establishing baselines followed by continuous monitoring of public attitudes towards the repository and its operations, while tracking the sources of change and their responsiveness to performance confirmation, to management practices, and to other elements of transparency.

How can a social science research program, such as the one above, contribute to the success of Adaptive Staging? It can contribute to the learning process, inform caution, supply perspective, provide understanding of necessary institutional enhancements, and establish procedures for improving the chances of public acceptance. The unprecedented time during which the repository will remain open—likely longer than the entire history of industrial economies—provides an unusual opportunity for social and institutional learning. Social science data and analyses can point to social and political fault lines that caution against misguided beliefs about institutional capability and public acceptance. The continual engagement of stakeholders and the public in the process of Adaptive Staging will ensure that their interests and concerns are not ignored at Decision Points about directions between stages. The success of Adaptive Staging is highly dependent upon institutional constancy and management continuity, requisites with an incipient understanding in the social science literature and amenable to more focused research The extended time over which the repository will remain open affords the opportunity to experiment with, and adopt mechanisms of, public participation that ensure broad enfranchisement and legitimacy, thereby improving chances of public acceptance.

Social science research has already contributed significantly to an understanding of the dynamics of the application of science and technology in the public sphere. It has demonstrated the importance of transparency and sustained engagement with concerned stakeholders to avoid policy gridlock while establishing the trajectory of future research. For example, it can provide economic and decision analyses to estimate the costs of Adaptive Staging, can point to its legal vulnerability, and can estimate the savings from avoiding path dependent, large-scale mistakes. There is, too, a sizable and rapidly growing literature on the translation of science into public policy and on mechanisms of public participation in that policy.

Based on the above reasoning, the proposed program of social science research, with its provision for societal and institutional learning, for increasing trust in implementing institutions, and for testing methods for stakeholder and public involvement, can enhance knowledge of the societal and institutional context of Adaptive Staging and thus increase the chances of repository program success.

- test facilities;
- pilot facilities; and
- demonstration facilities.

Test, pilot, and demonstration facilities are discussed below (see also Appendix G).

- **Test facilities.** The test facility is devoted to short- and long-term scientific experimentation aimed at improving scientific understanding, testing repository behavior, and providing contingency options without disrupting operations or compromising the integrity of the repository (EKRA, 2000, 2002). Test activities are also designed to anticipate changes in the characteristics of waste (e.g., different radioactivity content or thermal output). Repository-specific test facilities are located in the same host formation as the repository, but they are kept physi-

Sidebar 4.2 Mechanisms of Public Engagement and Participation

The social science component of the pilot stage could be devoted to testing alternative mechanisms for public participation. The evaluation process should lead to informed decisions over which mechanism or mechanisms might best satisfy the need for public involvement in implementing a geologic repository. The mechanisms selected would be incorporated into the full-scale operational phase. Pilot social science research should include evaluations of testing mechanisms for stakeholder participation and the development of techniques for monitoring changes in public confidence, trust, and institutional constancy (see Sidebar 4.1).

Examples of learning opportunities about participation mechanisms and techniques for stakeholder engagement are:

1. The continued engagement of the stakeholder advisory board during the pilot, the demonstration, and subsequent stages that would:
   -interact with the technical oversight group;
   -review new information collected and take part in the evaluations of stage performance;
   -have input at decision points about how to proceed when a stage is completed; and
   -advise on the pilot experiments of public involvement mechanisms.

2. The establishment of a social science component to the overall science program to:
   -systematically monitor the societal, economic, and political contexts of stage implementation (thereby providing an early warning system of potential fault lines); and
   -develop the program of experiments in the pilot stage to narrow down the number of public involvement mechanisms that would be implemented in the demonstration stage.

cally separate from the actual disposal areas to avoid compromising the integrity of the repository or interfering with construction or operations. Tests begin before the design is completed and can continue throughout the repository program until no further significant knowledge can be gained. Example activities may include testing of:

-alternative repository designs
-waste configurations
-thermal operating modes and strategies to change them
-new technologies for waste handling and emplacement operations
-thermal effects on the host rock
-stress response of the system (by using temperatures beyond the reference design)
-repository failure modes and weaknesses
-new materials for engineering barriers and backfills
-new monitoring technologies.

Tests can stress the components of the safety system beyond their design envelope or even to failure. The purpose is to study a full range of system behaviors Parallel to the scientific experiments should be societal research whose goal is to test alternative mechanisms for public participation. To ensure transparency, results from such a research program are shared with the stakeholder advisory board and the technical oversight group, who can also provide input on research activities.

• **Pilot facilities.** The purpose of a pilot facility is to test and evaluate the selected design and operating mode and to gather operational experience that can help to optimize full-scale construction and operation. The pilot allows improvement of safety and efficiency, as well as incorporating societal learning into the process. Pilot tests are not intended to deliver significant information on the long-term behavior of the repository system

Pilot activities are carried out in configurations increasingly close to those foreseen for the final facility. For instance, pilot activities can begin with non-radioactive waste before the license is obtained and continue with radioactive waste thereafter. At the end of the pilot stage a decision is made to affirm or revise the reference design and operation mode. This process may require a temporary delay in waste emplacement activities or even another pilot stage to confirm the expectation of the revised design and operation mode, if the information gathered during the pilot deviates from expectation. The full-scale operation may continue without any delay if the system performs as expected. A delay in the pilot stage need not delay waste shipments from generator sites if the implementer plans for a sufficient surface buffer storage capacity at the repository site. Pilot activities cease with the selection of the reference design and operation mode.

To ensure transparency, the decision-making process to begin and cease pilot activities is shared with stakeholders, the technical oversight group, and the regulators. Engineering pilot-scale activities are a normal feature of major technology developments. The committee uses the expression "pilot activities in social sciences" to indicate social science work taking place during pilot engineering activities (such as pilot construction, emplacement, or closure). Pilot activities in this sense could include experimentation to determine the public involvement mechanisms most likely to be effective.

• **Demonstration facilities.** Test and pilot activities are performed primarily to help the implementer develop and/or optimize the repository system. Demonstration activities, on the other hand, aim at increasing technical and public confidence in the chosen design and operation mode. The purpose of such a facility is to demonstrate a realization of the intended design of the repository and to allow particularly comprehensive monitoring of components and systems (e.g., emplaced canisters or borehole and tunnel seals) during the multi-decade operating life of the repository. Demonstration activities occur in parallel with repository operation until final closure. Demonstration activities can be initiated only when the reference disposal configuration has been defined (i.e , after the pilot stage). The pilot facility itself may become a demonstration facility.

Demonstration facilities may be separated from the main disposal areas to carry out intensive monitoring activities that could otherwise compromise the integrity or operation of the full repository Examples of demonstration activities include: monitoring to demonstrate that the waste or the surrounding rock is not being subjected to unacceptable thermal effects; monitoring to demonstrate that no unanticipated corrosion mechanisms affect the containers; and monitoring to control fluid pressure, flow, and composition. Part of the demonstration facility may also be backfilled to allow monitoring of the complete safety barrier system. Demonstration activities of the implementer are often aimed at increasing the confidence of other stakeholders, most especially the public. Obviously, no direct demonstration of long-term safety is feasible. The demonstration stage is also where demonstrations of candidate public involvement mechanisms are implemented.

Possible locations and timing of test, pilot, and demonstration activities are illustrated schematically in Figures 4.1 and 4.2. Test, pilot, and demonstration activities have an impact on the licensing and construction phases. As with Linear Staging, the implementer submits an application to construct the entire repository and presents the safety case for the entire waste inventory. Unlike Linear Staging, the implementer proposes, in agreement with the regulator, intermediate licensing stages.

This may be implemented in separate licenses, using license amendment procedures, or introducing intermediate permitting stages at a lower level; the choice will depend on the national regulatory framework of each country. For instance, the regulator may grant an initial license only for constructing the test and the pilot facilities. The license application acknowledges that the design and operating mode of the repository can change during the program and establishes a license amendment mechanism to modify the reference design. The regulator and the implementer agree on the type of design or operating mode change that requires a license amendment and the type that requires stakeholder input. Once the initial construction license is granted, the implementer constructs the surface facilities, the underground test areas, and the pilot facility. The test areas are constructed with different designs and test various thermal operating modes. The reference design is implemented in the pilot facility (called "Pilot/Demo facility" in Figure 4.1).

The regulator might grant the license with a condition to emplace first only a small amount of waste to be used in the pilot and test facilities. The construction of the remainder of the repository proceeds in additional stages. On the basis of the information gathered during the pilot and tests, the pilot facility is expanded or a different design is used to excavate a second disposal area, and the regulator removes the initial condition and allows emplacement of the remaining waste inventory.

The final design can be implemented in a dedicated demonstration facility. The implementer constructs additional sections of the repository with the standard design and operating mode unless further optimization is possible based on operational experience or information provided by the ongoing test activities.

There are several advantages to implementing test, pilot, and demonstration activities. First, they maximize learning and improve the repository program throughout the years of operation. Second, they may accelerate the schedule and lower costs of first waste emplacement because of the simplified and limited logistical requirements. Third, they lower the early investment in construction, because these facilities are less expensive and faster to build than a full-scale repository. Fourth, these activities address many challenges of geologic repository development (Table 4.1). Therefore, tackling these issues early can improve the chances for a program's success.

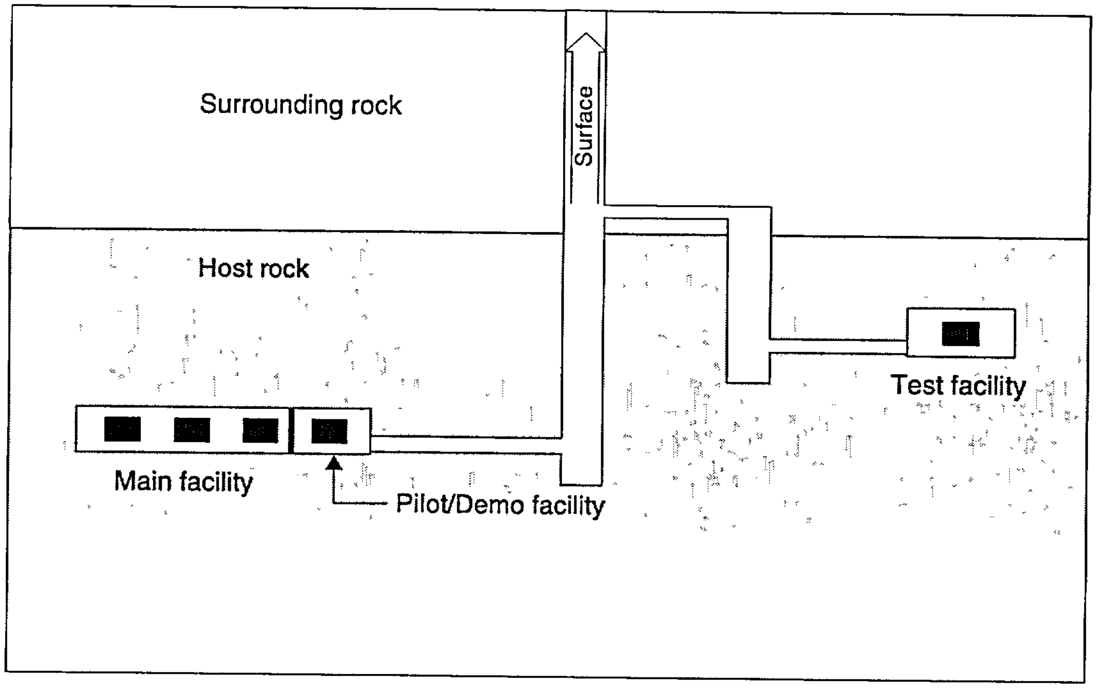

FIGURE 4.1 Cross-section of underground repository areas during the operational phase showing test, pilot, and demonstration facilities. The main facility can be backfilled or kept open until the end of the operational phase. Part of the demonstration facility may be backfilled to allow monitoring of the complete safety barrier system. This diagram is a modified version of the schematic concept proposed for a geologic repository facility in Switzerland, which also includes a pilot and a test facility. The nomenclature used here, however, differs from that used by the Swiss Expert Group on Disposal Concepts for Radioactive Waste (EKRA). SOURCE: Based on EKRA (2000).

The disadvantage of implementing test, pilot, and demonstration activities is the additional cost to construct, operate, and maintain the facilities. There will also be additional costs for monitoring the demonstration facility, which can be difficult to justify, because intensive short-term monitoring cannot provide direct evidence of long-term safety. Pilot, tests, and demonstration activities can delay the implementation of full-scale emplacement rates if results call for additional tests or waste retrieval. They can also reduce public confidence in the current understanding of the repository system if inexplicable results are observed—even those with no obvious safety implications.

4.2.2 Impact on full-scale operations

Major impacts of Adaptive Staging on full-scale operations are:

- emplacement rates increase (or decrease) if results from pilot and demonstration activities increase (or decrease) confidence in the system; and
- as the program progresses, early improvements are likely to lead to longer stages in the full-scale operational phase.

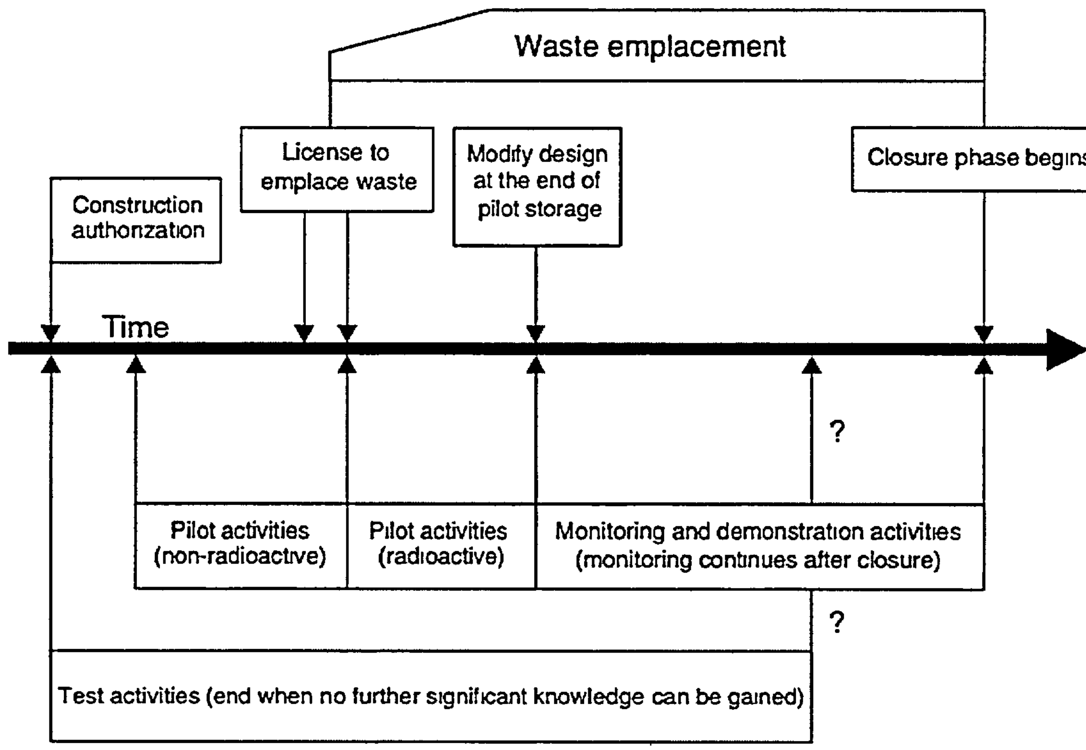

FIGURE 4.2 Example of possible timeline for implementing test, pilot, and demonstration activities in the pre-operational and the operational phase. The time when test activities will end is uncertain (indicated with a question mark). The timeline is not to scale.

The test, pilot, and demonstration activities increase the likelihood of uninterrupted full-scale repository emplacement operations. Although full-scale operations may begin later than with a Linearly Staged program, waste emplacement may end earlier, reducing overall costs (see the impacts on schedule and costs, Section 4.5). Introduction of new technologies or taking account of new knowledge becomes a normal activity throughout the repository lifetime; amendments to the reference framework are seen neither as a sign of failure, nor as proof that previous approaches were unsatisfactory, but rather as a mechanism for improvement.

If a major or partial adaptation of the system becomes necessary because of indications that performance will not be satisfactory, it would be sensible to suspend all or some operations until a remedy can be developed. This possibility is less likely when increased knowledge leads to an evolution in design or in operational procedures. To illustrate this the committee offers three hypothetical scenarios. Each scenario begins with full-scale operations proceeding smoothly, with drifts being constructed and waste being received and emplaced. A Decision Point to review experience and information gathered to that point is scheduled to occur in two years.[5]

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[5]These are illustrative scenarios, not prescriptions for action.

TABLE 4.1 How Pilot, Test, and Demonstration Activities in Adaptive Staging Can Address Challenges of Geologic Repository Programs.[a]

Challenges of Geologic Repositories	Pilot, Test, and Demonstration Activities Can Address These Challenges by
First-of-a-kind and complex	• improving the understanding of the repository system • allowing adaptation to unexpected findings more easily than the full-scale facility • removing the need for premature technical and operational decisions that could foreclose options • providing contingencies to the reference design without interrupting or disrupting repository activities • improving the monitoring and science and technology program to address technical, societal, and institutional difficulties (see Sidebar 4.1) • addressing unresolved questions of repository processes, unhindered by the demands of waste disposal operations • providing for systematic procedures for stakeholder and public involvement (see Sidebar 4.2) as well as for independent technical oversight.
Risk	• demonstrating the capability of safe transport and safe emplacement of radioactive waste as well as safe retrieval • testing system behavior under realistic conditions • performing non-radioactive tests and pilot activities before and during licensing • lowering risks and consequences because of reduced-scale tests • introducing Decision Points for re-evaluating, improving, and strengthening the safety case and reversing if needed
Public concern and controversy	• allowing testing of options or hypotheses suggested by all parties[b] (regulator, implementer, stakeholders), diffusing doubts and increasing confidence in the repository • providing an opportunity for the implementer and the regulator to demonstrate openness and accessibility • observing the performance of the repository by the demonstration facility throughout the duration of repository operation • providing early warning of unexpected phenomena in the demonstration facility • adding license conditions before moving to full-scale emplacement (This intermediate pilot stage may enhance regulator and stakeholder confidence in the implementer. It also demonstrates that regulatory oversight does not end with the first license) • systematically establishing transparent stakeholder, affected community, and public involvement procedures that emphasize continuous involvement (See Sidebar 4 2)

[a]These challenges are discussed in Section 1 2.1
[b]All test and pilot activities must not compromise the integrity of the repository, and those involving radioactive waste must first be approved by the regulator.

Scenario One: Approaching the Decision Point, all operational experience and new information indicate that the project is on track. The implementer decides to have the decision-making process run in parallel with waste emplacement and repository construction. The decision results in some minor recommendations to improve operations in the next stage. The implementer makes the correct judgment that no unacceptable or irreversible consequences can result from continuing operations during the Decision Point even though in principle the decision results in the reversal of some work.

Scenario Two: Two years before the Decision Point, a construction accident causes the implementer to suspend repository excavation and immediately begin an investigation to determine its cause. The implementer continues to receive waste and emplace it in existing drifts or buffer storage. The implementer schedules a new Decision Point to occur at the conclusion of the investigation of the accident. At this point the results of the investigation are evaluated, options are developed and evaluated, and a decision is made to modify construction methods to prevent future accidents. Repository construction resumes integrating the new method and the implementer plans a future potential Decision Point.

Scenario Three: The year before the Decision Point, the implementer develops a new technology for emplacement that promises cost savings with no compromise to safety. This knowledge is shared with regulators, independent technical oversight groups, and stakeholders. At the Decision Point the implementer obtains information on whether potential savings warrant immediate adoption of the new technology. The implementer decides to study and refine the new technology, through a pilot implementation and to consider adopting it at the next scheduled Decision Point. Meanwhile, waste emplacement continues with the "old" technology.

The point of these scenarios is to show that with Adaptive Staging management decisions depend on the nature of the information be introduced in the program. Adaptive Staging does not necessarily lead to undue delays.

4.2.3 Impact on closure and post-closure

The main impacts of Adaptive Staging on closure and post-closure phases are:

- a flexible schedule for closure and sealing is understood to be part of Adaptive Staging and not as an inability to make decisions;
- the schedule allows for a sufficient number of Decision Points to decide if, when, and how the repository is to be closed or monitoring ended;
- the repository remains open until all parties agree that it is safe to close it; and
- stakeholders and the technical oversight group can contribute to the definition of, and subsequent amendments to, the post-closure monitoring program.

As waste emplacement in the repository continues over decades, the repository's maximum allowable capacity will be approached or reached. Reaching this operational milestone, the transition is made from the operational phase to the closure and post-closure phases, which will trigger a number of activities and decisions, as depicted in Figure 4.3. The decision tree shows some of the critical and anticipated Decision Points in this transition and highlights the important role of monitoring and safety. (Some impacts of Adaptive Staging on closure and post-closure activities are also discussed together with the impacts on monitoring and safety in Section

4.6 and Section 4.8, respectively.) Figure 4.2 reflects the assumption that both the science and the monitoring programs will continue at least up to repository closure.

Approval of closure implies that the safety case has been updated and demonstrated and that new knowledge has been integrated to increase confidence in the long-term safety of the repository. Closure also implies that waste will not be retrieved for future use or reprocessing and therefore must be safeguarded from external intrusion. (As noted previously, it is conceivable that programmatic waste retrieval can be attempted after closure—perhaps in response to some previously undetected flaw in the repository or because some future technological breakthrough will make reprocessing of high-level radioactive wastes viable and desirable.) The need for safeguards and the desire for continued assurance may require decisions to be made about monitoring and whether to emplace surface barriers or markers to warn future generations of the presence of hazardous radioactive materials in the subsurface.

The closure process can also be performed in a staged manner. Closure will require construction of the final engineered barriers, including buffers, backfills, and seals. After final construction of engineered barriers but before decisions are made about closure, some period of monitoring of the seals should be added to the monitoring program to assure that, at a minimum, the seals are stable and effective. After site closure has been completed the post-closure stage begins and continues as long as necessary. Currently, there are no regulatory requirements for societal or government activities during the post-closure stage. This is partly because the persistence of institutional control so far into the future cannot be predicted or assured. This lack of assurance is one reason why the repository should not impose on future generations any obligation for indefinitely long, active institutional control. A parallel implication is that the facility will be judged to be so safe that it will not (and should not) require such indefinite control.

Nevertheless, entering the post-closure phase requires institutional control at least up to that time. To attain this stage, confidence in long-term safety will be very high. Even though confidence in safety is high, some small degree of risk and uncertainty inevitably remains. A range of options for continued safeguarding should be considered, including planning for the maintenance of a monitoring program that would continue indefinitely into the future as long as it is deemed necessary and important to future generations. Perpetuation of such a program presumes that society's awareness of the existence of the repository persists. The likelihood of this can be enhanced through use of markers and thoughtful and thorough record-keeping and documentation. Rationales for decisions can be incorporated into this long-term institutional memory. Site security also can be maintained to minimize the possibility of human intrusion—either intentional or accidental.

When future generations of stakeholders are assured of repository performance and safety, they can make the decision whether to cease monitoring activities. In the far future it is less desirable to envision abandoning the repository because of either a gradual loss of institutional persistence or a major political or societal upheaval. Closure with no monitoring based on high confidence in the repository's inherent safety is clearly the goal. Adaptive Staging is a philosophy that should be able to successfully guide repository managers over many generations to that final milestone.

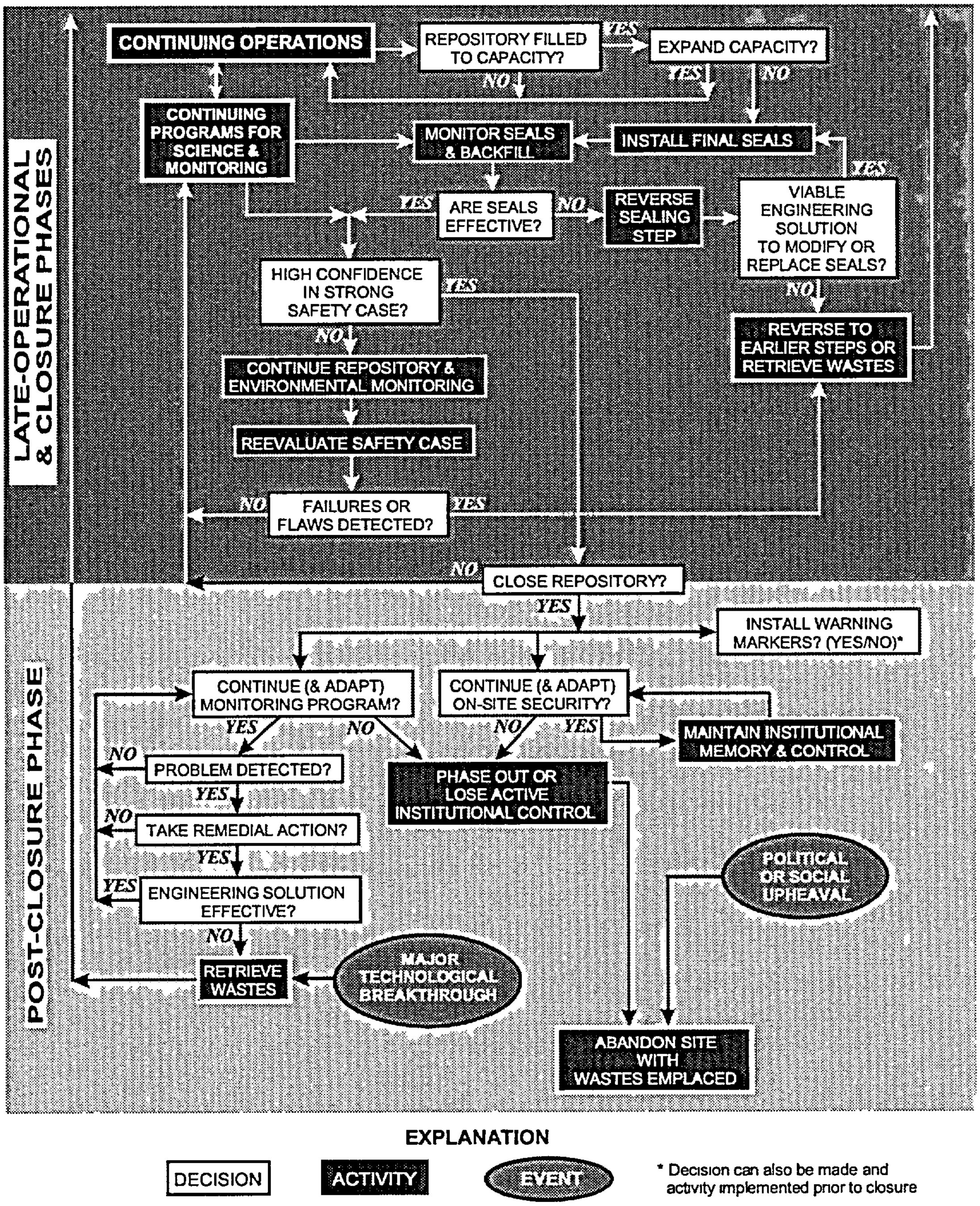

FIGURE 4.3 Committee's examples of decision tree and activities during the late operational, closure, and post-closure phases of a repository program using Adaptive Staging. A variety of monitoring activities is ongoing during these phases.

4.3 Impact on buffer storage requirements

Adaptive Staging has the following impacts on buffer surface storage requirements:

- higher buffer storage capacity may be required at or near the site compared with Linear Staging; and
- the implementer must work with waste storage facility managers to optimize surface storage requirements.

Adaptive Staging's flexibility and reversibility may require a higher buffer surface storage capability located at or near the repository site to keep open various options for emplacement schedules. Sufficient buffer storage provides the flexibility to choose among wastes types (thermal blending), for managing emplacement and for ensuring a place to which waste can be credibly retrieved, should the need arise. Such buffer storage also provides a flexible mechanism to separate waste acceptance from waste disposal. Increased buffer storage allows for flexibility in the system, and affects the need for at-reactor storage and transportation capacity. A cost- and schedule-driven Linear Staging approach tends to minimize buffer storage and aims for "just-in-time" delivery of waste.

The main negative impact of Adaptive Staging is the cost of the surface storage. In a Linear approach that couples shipment rates with underground emplacement rates, only minimum surface storage capability is necessary. If waste emplacement and construction do not encounter any obstacle (i.e., the repository is constructed and waste is emplaced according to the pre-determined schedule and there is no need to retrieve it), Linear Staging is probably more economical than Adaptive Staging.

In many programs there is reluctance to implement a high-capacity buffer storage, especially if the storage facility operates before the repository is functional, out of societal fears that the buffer storage facility could become a permanent surface storage facility. This concern can be alleviated if the regulator grants the repository construction authorization before the surface facility is built and if the regulator grants the licenses to receive and emplace waste in the repository before the buffer storage facility is operational. In some countries, such as the United States, the law forbids the implementer (the Department of Energy) to begin any construction of storage facilities or acceptance of waste at the site before the regulator (the Nuclear Regulatory Commission) grants the licenses to construct the repository and emplace the waste.[6]

4.4 Impact on transportation

The main impacts of Adaptive Staging on transportation are that:

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[6]However, the need for a license does not imply that Adaptive Staging requires changing regulations. It means that the implementer must specify the use of buffer storage in the license application.

- waste transportation to the repository site can begin earlier, perhaps at lower cost, with a small amount of waste;
- waste transportation rates are more flexible, because they are independent of underground emplacement rates; and
- the buildup to full operation affords opportunities to investigate alternative transport routes and methods.

Adaptive Staging implies that the timing, size, rate, and modes of transportation will be integrated with buffer storage and repository operations. In fact, implementing a complete transportation system is itself a major, complex project that can meet the criteria for application of Adaptive Staging (see Section 2.5) and could benefit from this approach.[7] Adaptive Staging will result in a slower buildup of transportation rates. However, by decoupling waste emplacement from waste acceptance, transportation can begin earlier, perhaps at lower cost and with a more flexible road transport mode. Trucks could begin transporting waste to the repository rather than waiting until a transportation system is in place for full-scale operations. If the transportation system is staged, waste emplacement for pilot and tests can begin as soon as the repository is licensed. Adaptive Staging provides opportunities to learn about transportation routes, modes, and logistics and their progressive integration in the program, as well as about public concerns and attitudes. The final transportation program may then incorporate more safety features and follow optimized routes, be more cost-effective, and better address public concerns.

4.5 Impact on program schedule and costs

The impacts of Adaptive Staging on program schedule and costs are:

- up-front investments for test and pilot facilities;
- increased costs for high capability of buffer surface storage;
- added time and costs for Decision Points;
- investment for a continuing monitoring program (see Section 4.6); and
- investment for a continuing long-term science and technology program (see Section 4.7).

As noted previously, the actual impact of Adaptive Staging on the overall program's schedule and costs is uncertain because Adaptive Staging has never been tested in the context of geologic repositories.[8] The *a priori* cost-benefit assessment of a flexible management approach, such as Adaptive Staging, compared to that of

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[7]This report does not address waste transportation. A National Research Council study on transportation of radioactive materials is under way.

[8]Kai Lee noted that "The adaptive approach rests on a judgment that a scientific way of asking questions produces reliable answers at lowest cost and most rapidly; this may not be the case very often. As Carl Walters has emphasized, adaptive management is likely to be costly and slow in many situations (e.g., Walters, Goruk, and Radford, 1993)" (Lee, 1999; p.3)

Linear Staging is a recurrent problem in research in economics and decision theory. The committee is not in a position to analyze specific cost implications.

Adaptive Staging may appear to lead to greater costs because of its cautious beginning. However, Adaptive Staging reduces the need to commit prematurely to costly program elements such as materials and technology purchases or full-scale construction. This gradual approach may lead to faster and less expensive resolution of problems. Program revisions made at each stage, based on previous stage experience, may avoid longer-term, irreversible difficulties that could be more expensive to solve and could actually slow progress. The potential cost problems involved with an inflexible Linear approach have been summarized by Holling:

> ".. even when errors are not, in principle, irreversible, the size of the original investment of capital and of prestige often makes them effectively so. This behavior has its roots in a very human characteristic of industrial man: we do not like to admit and pay for our past mistakes; we prefer to correct them. And the consequences of correcting an inflexible plan [are] often increasing investment, increasing costs for maintaining and controlling the system, and progressive foreclosure of future decision options" (Holling, 1978; p 8)

Second, there needs to be analyses of the cost impacts of Adaptive Staging as it affects the schedule of the early operational phase. If a license is granted, Adaptive Staging is likely to reduce the time and costs to emplace the first high-level radioactive waste. This allows an earlier start to confirmatory testing and optimization of operations. The cost incurred to operate a test facility and/or a pilot facility is appreciable but smaller than full-scale repository costs. Thus, if one of the programmatic benchmarks is the point when emplacement begins, it is likely that Adaptive Staging reduces costs to reach this milestone, whereas with Linear Staging full-scale facilities are built before beginning waste emplacement.

Third, discount rates must be considered. This more debatable point is that savings using any discount rate may reduce costs in an Adaptively Staged program since major construction costs for building a full-scale facility arise later than if the repository is built all at once.

Fourth, there is the need to assess the effects of public resistance. Public resistance adds delays and thereby increases the costs of implementation. Public concerns, opposition, and controversy are recognized challenges to a geologic repository program (see Section 1.2). Thus, while the flexibility of Adaptive Staging may lead to short-term delays and added initial costs, the medium-term effect may be a cost saving because of enhanced acceptance of the repository.

Finally, any discussion comparing the schedules for Linear and Adaptive Staging must consider the time necessary to gather information. Linear Staging needs information to plan the whole project before it starts. This is what NASA attempted before it started the development of the International Space Station (Appendix C). For a complex, controversial project such as a repository development this might mean years of research and testing before a Linearly Staged project could begin. Adaptive Staging, making small, reversible, incremental decisions allows both time for learning while early stages are accomplished, and incorporation of new information into options for later stages. Thus, an Adaptively Staged project might start and end earlier than a Linear project, although this cannot be proven.

In summary, Adaptive Staging need not necessarily increase costs; it may do so in the short run, but it may also serve to avoid expensive errors over the long-term or reduce delays (hence costs) caused by programmatic inefficiencies or societal conflicts. The low-cost estimates of developing projects with Linear Staging often prove unrealistic because of the assumption that the project will proceed as planned in advance with no surprises or disruptions. NASA's Space Station offers an illustrative example: managed Linearly, it continues to experience cost growth and capability shrinkage due to unanticipated factors, as described in Appendix C.

4.6 Impact on the monitoring program

A credible, comprehensive monitoring program is an integral part of any management approach for repository development, but takes on increased value and importance under Adaptive Staging because monitoring allows for systematic learning. The impacts of Adaptive Staging for the monitoring program are:

- monitoring takes on enhanced importance because it is a primary method for obtaining data required to make decisions;
- monitoring activities may increase during the pre-operational and operational phases;
- effort must be devoted to developing a monitoring program that satisfies the attributes of Adaptive Staging;
- mechanisms must be developed to ensure that the monitoring program has sufficient scientific credibility and lack of bias;
- the monitoring program may include a wider array of measurable parameters, including future societal, institutional changes, and economic impacts;
- developing a monitoring program involves cost optimization and organization of financing;
- the monitoring program design must include redundancy; and
- monitoring must link to both the performance confirmation[9] and to the long-term science and technology programs.

The first five impacts are specific to the implementation of Adaptive Staging. The last three address crucial aspects of a monitoring program that are equally valid for Adaptive or Linear Staging. A discussion of each impact follows.

First: before construction and operation, monitoring is conducted over the entire site. This monitoring activity produces a baseline database characterizing the conditions, properties, and behavior at the site before any disturbance is caused by repository operations. Baseline conditions are established during the site characterization stage. Baseline measurements provide the foundation for making decisions related to future system performance. Intensive *in situ* monitoring of the pilot disposal rooms, their environs, and their engineered barriers provides essential data for scaling up to a fully operational activity. The pilot and test facilities also serve as a testing ground for monitoring methodologies. During the operational phase, monitoring is used to follow the performance of the repository (as part of the

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[9]The performance confirmation program is a process to test and evaluate whether the repository system is working as expected and within the acceptable safety margin.

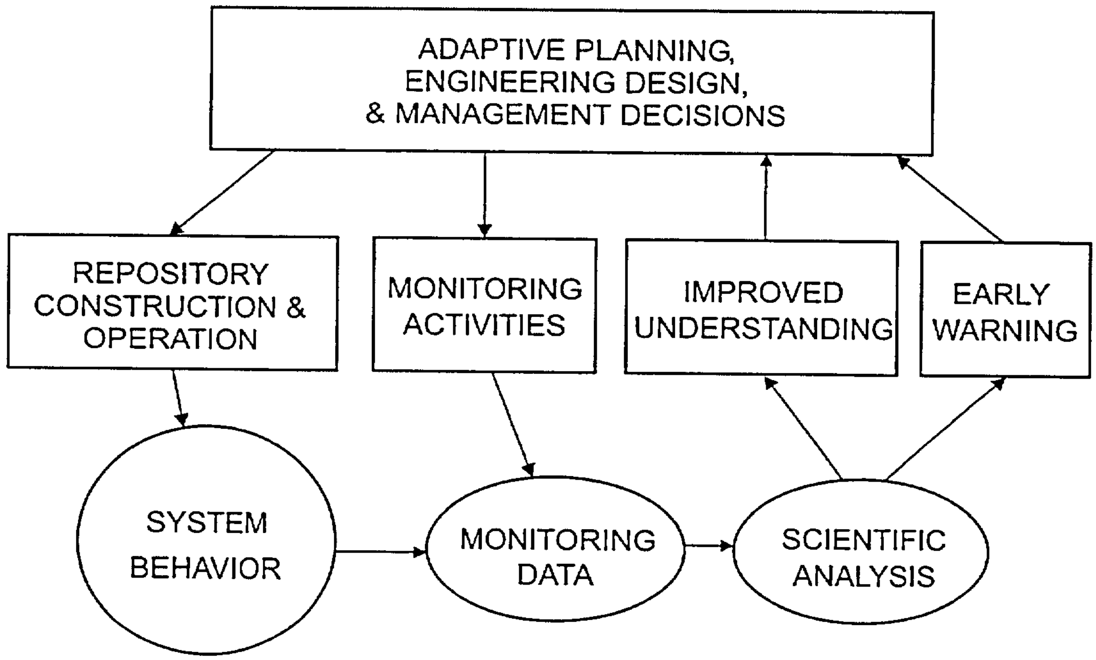

FIGURE 4.4 Role of monitoring during the operational phase of the repository. This figure indicates how monitoring interacts with management, construction, and operation activities and with the long-term science and technology program. Repository operations affect the system's behavior; changes in behavior, in turn, are detected by monitoring.

performance confirmation program). Figure 4.4 illustrates the role of monitoring during the operational phase and indicates how monitoring interacts with management, construction, and operation activities and with the science program.

The post-closure monitoring program might be a scaled-down version of the pre-closure monitoring program. Most likely, *in situ* repository monitoring would be precluded during the post-closure stage to ensure repository integrity. For example, monitoring may be limited to observation wells, geophysical surveying techniques, and remote-sensing methods. A further example of post-closure monitoring is ensuring that the repository seals remain effective and stable. By the time the post-closure stage begins it is likely that unanticipated monitoring technologies will be available for use.

Post-closure monitoring can continue for as long as institutional control and memory persists and can provide input for maintaining confidence in system performance. An Adaptively Staged monitoring program will continue for as long as deemed necessary by the implementer, regulator, and stakeholders.[10]

Second: monitoring by definition is the primary tool for obtaining data required for systematic learning; that is, monitoring provides information for essential repository management decisions. In the context of an Adaptively Staged geologic repository program, the monitoring program should feed into the Decision Points. It is central

[10]Monitoring in this context is not intended to be a substitute, but rather a complement to the safety of the system of natural and engineered barriers

to Adaptive Staging that monitoring of repository performance can make a difference in repository operations, in comparison to Linear Staging, in which monitoring is used to assure compliance rather than achieve improvements or warning of trouble. Monitoring is intended to provide a safeguard against poor predictive accuracy of models, because the ability to make accurate long-term predictions of material and system behavior is not proven. Another purpose of monitoring is to assess long-term environmental changes and their impact on the repository environment. If a climate change, or seismic or volcanic activity, alters the conditions on which the safety case was based, then the implementer must know this and respond accordingly.

Because monitoring geologic repositories is also a first-of-a-kind endeavor, monitoring approaches must be designed with flexibility in mind. Monitoring can be reduced or simplified if confidence in safety increases, or monitoring can be intensified or shifted to new targets if new questions and concerns arise about component or overall repository performance. During the long operational life of a repository, new monitoring technology will likely lead to modifications of the monitoring program. The monitoring program extends throughout the repository program and well into the post-closure phase. As new data and knowledge are gathered over time, the monitoring program needs periodic re-evaluation and adaptation to maintain efficiency and effectiveness. Monitoring a complex system such as a geologic repository has technological challenges (see Appendix E). Hence, the development of the monitoring program itself could benefit from Adaptive Staging, because many decisions are predicated on previous ones (see Figure 4.3).

Third: the monitoring program requires all attributes of Adaptive Staging, in particular integrity and lack of bias. Integrity and lack of bias are key attributes in the context of a monitoring program for a geologic repository, because the monitoring data are key to assessing system behavior and whether the program is meeting established safety criteria. Part of the monitoring program may be overseen or even directed and performed by stakeholders and institutions that do not have a direct mission to build, operate, or regulate the repository and that have a strong likelihood of maintaining continuity of purpose. Transparency, integrity, and demonstrated openness to views of others are also enhanced by negotiating the details of the design and operation of the monitoring program with stakeholders, the technical oversight group, and the regulator.

Fourth: the transparency and auditability of the monitoring program, combined with a mechanism to seek and incorporate stakeholders' and regulators' input can help to promote confidence in the ability of the repository to function as intended. Additionally, monitoring provides an early-warning system to alert implementer, stakeholders, and regulators to potential problems or questions that may affect repository performance and that must be resolved (Figure 4.4).

The monitoring program communicates and seeks input from the stakeholder advisory board and the technical oversight group to expand the knowledge base and to establish scientific credibility. Scientific credibility can be maintained and costs kept justifiable only if potential traps are avoided. In a recent workshop (EPRI, 2001), several such caveats for the monitoring program were noted. The more relevant of these are paraphrased as follows:

- do not agree to do what cannot be done with available technologies;
- do not claim that safety can be demonstrated based on monitoring of limited duration or extent;

- do not require unattainable accuracy or precision in measurements; and
- do not assign an excessive level of conservatism on a subsystem simply on the basis that it appears to be relatively easy to stay within the bounds.

Fifth: the social and institutional context of the program may change and undermine the design of the program—for example, by altering transportation capabilities for delivering waste to the repository. The implementer is responsible for sensing and alerting authorities and society to emerging incompatibilities between social conditions and the mission of safely disposing of radioactive waste. The committee terms this type of monitoring "societal monitoring." Examples of societal monitoring are changes in stakeholder attitudes or confidence in repository performance, trends in public acceptability and in stakeholder participation, losses in or maintenance of institutional memory, and audits of those institutions having critical responsibilities relative to the repository program. Information gathered from social monitoring should also be useful in preparing contingency plans to assure that interruption of the program could still lead to safe shutdown of facilities and handling of wastes left unemplaced. Many aspects of social monitoring and assessment are new, and there remain uncertainties as to what parameters to measure and how to measure them other than by survey methods. This is part of the basis for recommending the need for additional research in these areas. The monitoring program may also include monitoring the economic impacts of the program (see Sidebar 4.1).

Sixth: the monitoring program requires a tradeoff between cost (as related to comprehensiveness) and robustness (or reliability). Monitoring cannot observe all parameters at all locations at all times. It is a sampling problem, partly statistical in nature. Adaptive Staging allows the monitoring program to adapt based on sound science and engineering practices. However, Adaptive Staging implies that stable financial resources are dedicated to the monitoring programs to allow continuity and maximum benefits from results.

Seventh: the monitoring program must include redundancy in design because data gathered from the monitoring program are critical to decision-making and provide assurance that the repository is functioning as expected. If one device fails, a system must be in place to prevent this failure from compromising the integrity of the monitoring program. Even in the absence of failure, a redundant monitoring program can provide correlation on measurements. Multiple methods of acquiring information assure that critical measurements are not overlooked or lost, or that faulty measurements are detected. Instrumentation that fails is replaceable at least before closure of the repository. Monitoring data must also be stored and preserved in ways that will assure wide availability and recovery of records far into the future. Future generations will then have the opportunity to review monitoring plans and results and make suitable adjustments. The monitoring methodology must be adaptable to information gained during the course of the monitoring program. It involves techniques of various levels of sophistication. Baseline measurements are sufficiently diverse and frequent to anticipate future needs in performance confirmation.

Eighth: an Adaptively Staged monitoring program is strongly linked to and integrated with the performance confirmation program and the long-term science and technology program in the following way (see Figure E.2 in Appendix E). Monitoring provides data for the performance confirmation program and to improve the understanding of the repository system's behavior. The performance confirmation and the long-term science and technology programs dictate the data needs from the monitoring program. In turn, the monitoring program tests model predictions and evaluates key uncertainties. The long-term science and technology program may also provide updates in monitoring technologies.

The committee notes a number of knowledge gaps associated with the implementation of a cost-effective, technically sound, and confidence-building monitoring. Questions to be addressed are shown below.

- Who decides what technical data are necessary?
- Are the technologies to obtain necessary monitoring data available?
- How extensive should a monitoring program be?
- What are the mechanisms to communicate results to stakeholders and the general public?
- What kind of data would enhance public confidence?
- How can duplication or disruption of the implementer's monitoring efforts with the participation of stakeholders and the regulator be avoided?
- What conditions assure the institutional capability to conduct monitoring over the relevant time periods?

In sum, Adaptive Staging's continuous, systematic learning requires an ongoing program to monitor the engineered and natural barriers of the repository environment and a concurrent long-term science and technology program to (1) analyze and interpret the system behavior; (2) recommend system improvements when provided with new information; and (3) address knowledge gaps. Adaptive Staging provides an opportunity for the social sciences to perform parallel monitoring functions and other relevant research to enhance the societal and institutional aspects of program development.

Some of the important new scientific and technical information will emerge from technical monitoring of the system, some will arise from specific studies before and during the operational phase, and some will result from experience gained in all stages. Continuous learning is also a goal for the social sciences, which means that a social science program is designed for learning, providing feed back from what has been learned, and adapting. This goal can be accomplished by evaluating practical experience gained during prior stages and by performing custom-designed social science research.

4.7 Impact on the long-term science and technology program

In the committee's view, a long-term science and technology program that includes both research and development is an integral part of a geologic repository program. In the context of this science and technology program, Adaptive Staging implies:

- maintaining a continuing long-term science and technology program until closure;
- developing research plans that address the critical technical and societal issues;
- integrating continuously the results;
- retaining qualified staff in the program; and

- integrating the scientists' input into the monitoring program.

In Linear Staging the role of a science and technology program, particularly after licensing, might be viewed as minimal. While some research might continue to confirm repository behavior, the emphasis is on implementation of the reference case with the minimal changes. For example, the choice of a waste packaging material becomes fixed once a license is issued. Therefore, further research on packaging material is not needed.

With Adaptive Staging, the waste packaging material compositions and properties become the subject of review if new information justifies it. The four possible outcomes of the review are: (1) judging the previously chosen materials to still be the best available; (2) using a different or a better material in the future; (3) replacing material already in place in the repository; or (4) taking no action until more information is available. A better material can be one that yields substantial savings, even if overall repository performance is not improved.

A robust, sustained science and technology program is consistent with the commitment to the systematic learning attribute of Adaptive Staging. The long-term science and technology program reflects the implementer's questioning attitude, searching for vulnerabilities and better approaches to achieving repository goals. In Adaptive Staging, a long-term science and technology program is needed to: (1) reduce known uncertainties;[11] (2) develop the capability for responding to "surprises" (i.e., unknown uncertainties or discoveries);[12] and (3) improve or identify weaknesses of the safety case (and help address them) by providing additional evidence that the repository is behaving as predicted; and (4) further develop, refine, or test aspects of the performance assessment methodology.[13]

The long-term science and technology program focuses in part on hypothesis falsification. If the hypotheses[14] are not verified and new information has a significant effect on safety or confidence in safety, then either a) the program is revised, possibly by reverting to an earlier stage, or b) the safety case is changed in light of new information (e.g., showing that a worrisome failure scenario is in fact impossible). A viable science program will assess the consequences of an unverified hypothesis. If consequences have no bearing on safety or are only of academic interest, then no response is needed. Making changes in light of evidence that casts

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[11]Examples of known uncertainties include: corrosion of spent fuel and glass; thermodynamic properties of geologic materials; behavior of geologic materials and natural barriers; and processes, mechanisms, and pathways that control groundwater flow.

[12]Examples of research capabilities for responding to unknown uncertainties include: research on new types of waste forms and waste packages materials, monitoring technologies, storage and retrieval of data over long time scales, and/or new types of public involvement mechanisms.

[13]For example, some underlying conceptual models can be tested and evaluated by analysis of natural systems that are analogs to the repository system. Examples of natural systems used for comparison include the groundwater composition at the uranium ore deposit of Bangombé (Jensen et al., 2002) and the loss of minerals at the Peña Blanca uranium ore deposit (Murphy and Cadell, 1999). An extensive database that can be used to compare code results with observed data is available in the literature.

[14]For example, hypotheses in geohydrology, engineering, societal context, security, and costs can be subject to hypothesis falsification.

doubt on a hypothesis is a matter of standards of disproof; these standards could be established by mechanisms such as peer review or repeated testing and reassessment within the scientific community.

The science and technology program can also assist in improving institutional relations, and perhaps public confidence, by obtaining information important to stakeholders and the general public. In the committee's opinion, a strong science and technology program is needed not only at the beginning of a program but also throughout the entire project, at least until closure and possibly after closure as well. Continued improvement of methods and techniques will likely allow better data to be included in the program.

Adaptive Staging acknowledges the possibility for unanticipated events during the course of repository development and is prepared to address them by maintaining a research capability throughout the repository program. Research capability means that the implementer has an ongoing program that focuses on the most likely areas of need. To be effective, the science and technology program must be a long-term effort that maintains continuity of purpose and encourages tenure of technical and management personnel.

Therefore, Adaptive Staging requires leadership to maintain the institutional capability to conduct such a science and technology program over the relevant time periods. It also requires hiring and retaining qualified scientific staff to function as a sustainable pool of knowledge for long-term science and technology programs. It requires a highly qualified staff to analyze and interpret data collected by the monitoring program and to provide input and feedback into the monitoring program. Hiring and retaining a body of highly qualified scientists increases program costs. Maintaining a long-term science and technology program can be challenging when competing with budget allocations for pressing operational issues.

4.8 Impact on safety

Adaptive Staging has the following impacts on safety:

- it raises the importance and requires frequent updates of the safety case and encourages continuing open review of the safety case, leading to improvements of the repository system or even to rejection of an unsuitable site; and
- it takes a more cautious approach to radiation exposure control and accident risk for workers.

Safety refers here to worker and public safety. A key feature of Adaptive Staging is the iterative review of the safety case. At Decision Points between stages, the implementer conducts a systematic re-evaluation of the safety case when relevant new information is gained during the previous stage. Even when no new negative information is gained, the review provides additional confidence that the adopted design is satisfactory. When improvements are in order, they can be implemented as part of the normal course of operations and not viewed as a detrimental deviation from previous plans.

The re-evaluation of the safety case, in turn, serves to guide the collection of data in a subsequent stage. A critical aspect of safety case review is that the program not only specifies new data to collect but also allows for hypothesis falsification and testing concerning repository performance. Over time as stages are completed, the ability of the program to predict performance improves. This improvement, in turn, increases confidence in the robustness of the safety case.

The committee re-emphasizes that the re-evaluation of the safety case neither implies repeated questioning of earlier decisions, nor necessarily leads to a pause in program activities, and in no case is it an excuse for unnecessarily delaying decisions. Its purpose is to examine the current situation to know how to proceed, not to belatedly question how one arrived at the current situation. The implementer ensures that any major changes in original program goals or strategy are based on new knowledge and new understanding of the system and not from incremental changes.

The activities associated with the construction and operation of a geologic repository are extensions of familiar industrial activities in mining, handling heavy equipment, and handling substances that emit strong ionizing radiation. The unique aspects in repository operations are that the heavy waste packages that emit the radiation must be removed from a controlled shielded environment at the surface to the underground drifts (shielded or unshielded). To some extent remote-handling techniques may be required. These activities can begin in a pilot stage, first using simulated waste and then actual waste to develop the best techniques for handling the waste effectively, while keeping worker radiation exposure as low as reasonably achievable (ALARA). These techniques are then used for the full-scale waste handling and emplacement.

The use of pilot facilities is also valuable for minimizing the risk of industrial accidents, a serious concern for heavy operations in a repository. The development of low-risk designs and procedures requires the development of a safety culture in repository management and workforce (see Section 2.2). Experience with large industrial operations and with operating repositories, such as the Waste Isolation Pilot Plant, show that hazards and accidents can be minimized when the management and workforce adopt a safety culture that puts safety at the forefront of operations. With Adaptive Staging this safety culture permeates the management of the implementer and its workforce, and contractors.

Management implements incentives for the workforce to ensure that employees remain involved in the safety program. Safety management tools already exist; for instance, the environmental management standard ISO 14001 is used in a number of facilities (e.g., in the Waste Isolation Pilot Plant in the United States and in the Swedish program). These tools incorporate many of the attributes of Adaptive Staging. They promote continuous learning and periodic re-evaluation, provide for independent auditing and reporting, and are a way to provide transparency in the important issue of operational safety (ISO, 1996a,b).

When these attitudes are instilled into the physical aspects of the operation, they become part of the safety culture of the organization, leading to a pervasive questioning attitude about how and why things are done. Management and workers look for vulnerabilities in the present mode of operation and develop a conduct of operations that will ensure continuous safe behavior.

4.9 Impact on security

The committee identified no significant negative impacts of Adaptive Staging on security. There are two fundamental issues to address when considering the impact of Adaptive Staging on the security of any country. First, for countries whose national security depends on nuclear activities there must be a secured management process in place for handling waste. Thus, there are national security implications arising from the disposal of some defense-related high-level radioactive waste when such waste contains such materials as highly enriched uranium or plutonium. The Adaptive Staging approach offers additional flexibility before emplacement to choose or blend wastes according to their security requirements or their radioactivity content and thermal throughput.

Following the tragic events of September 11, 2001, attention must be given to the impacts on program goals and objectives that relate to security of radioactive wastes and the increased awareness of their vulnerability to terrorism. A number of organizations and individuals have raised issues with regard to security that may have a direct or indirect bearing on repository programs. Among these are potential vulnerabilities at generator sites, particularly spent fuel in pool storage at nuclear power plant sites, and vulnerabilities during transportation of spent fuel from plant sites either to a consolidated interim storage facility or a repository. These issues have been discussed in a recent National Research Council report on counterterrorism (NRC, 2002b).

As noted previously, Adaptive Staging can slow the initial pace of underground waste emplacement. At the very least, it removes the certainty of placing the high-level waste underground by a given date. The inevitable pressures to accelerate the emplacement of waste, due to nuclear proliferation or terrorist concerns, counters the tendency of Adaptive Staging to proceed in a more deliberate and cautious manner. Adaptive Staging may lead to longer periods in which the waste is more accessible to humans. If the time scales become very long (decades to centuries), then institutional stability cannot be guaranteed. In this case, security could become a concern. However, even under the most optimistic waste emplacement schedules, significant amounts of wastes are likely to remain at reactor storage sites for decades.[15] Furthermore, waste must be transported to the repository site regardless of how the repository program is organized. If rapid removal of high-level waste from surface storage at reactor sites is considered to be necessary to address terrorist threats, then other solutions beyond a geologic repository program will have to be considered. From this perspective there appears to be no significant difference in impact on security between Adaptive Staging and Linear Staging.

4.10 Impact on the regulatory framework

Adaptive Staging has the following impacts on the regulatory framework:

- it increases regulatory review steps;
- it requires flexibility from the regulator in formulating and applying regulation;
- it requires flexibility in the license amendment process;
- it provides the regulator with increased flexibility to amend regulations if experience warrants; and

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[15]In the United States anticipated quantities of spent nuclear fuel exceed the statutory limit of the proposed repository at Yucca Mountain (see Chapter 5).

- in enhances stakeholder confidence in the regulatory process by increasing transparency.

To the extent that repository design, construction, and operation options are kept open beyond the initial license application, the licensing process with Adaptive Staging might become more complex for both the implementer and the regulator—for example, if the implementer builds into the license application mechanisms to change the repository design and operating modes on the basis of information gathered during the early operational phase. In spite of the added complexity, Adaptive Staging may be beneficial to the regulatory framework. Regulating a first-of-a-kind repository is a process of gradual learning and refinement. This is recognized by the French safety authorities who have prepared a series of non-mandatory basic safety rules (*règles fondamentales de sûreté*) designed to evolve as new information becomes available. It is unrealistic to expect that a regulator can set forth regulations that would govern activities for over a century with no need for modification. For example, in the U.S. during the 20 years since enactment of the Nuclear Waste Policy Act, there have been at least two major changes[16] in statutory requirements and major changes in the regulations promulgated by the Environmental Protection Agency, the Nuclear Regulatory Commission, and the Department of Energy. The knowledge available at the time of construction authorization is less complete than in subsequent phases. The Adaptive Staging approach encourages the acquisition of additional knowledge and allows regulations to develop and to take account of new knowledge gained during the multi-decade repository development program. Adaptive Staging may, therefore, address the challenge of the "regulator's dilemma," which refers to the challenge of making regulatory decisions in the presence of uncertainties, some of which are not resolvable (NRC, 2001).

The staged approach to licensing allows the implementer to expand, and the regulator to review, the knowledge base and the safety case at each licensing phase. Adaptive Staging emphasizes the importance of providing a traceable and auditable record of decisions, thereby increasing the transparency of the licensing process. The regulator and implementer, therefore, have the opportunity to strengthen stakeholder confidence that the program is based on a robust disposal concept, good engineering and technology, and a suitable site.

Even when a particular country's legal system requires prescriptive regulations for a repository, there is normally sufficient scope for flexibility at the level of detailed regulatory guidance, decision-making, and inspection programs. Adaptive Staging can be compatible with a regulatory system if that system is flexible and responsive to change. Adaptive Staging can be effectively applied only if the license amendment process is not overly complex or long, and the implementer has the possibility, if justified, to continue the program during the amendment process.

[16]The statutory changes are the 1987 amendment of the Nuclear Waste Policy Act and the Energy Policy Act of 1992.

4.10.1 Regulatory obstacles

Adaptive Staging may place obstacles in the regulatory process for both the implementer and regulator (e.g., NRC, 2001). From the implementer's point of view, Adaptive Staging may be seen as causing more intensive regulatory oversight, which may delay the repository program. From the regulator's point of view, Adaptive Staging requires flexibility and acceptance of the uncertainty involved in permitting or licensing individual stages in a somewhat open-ended program, albeit one supported by a safety case for a full repository. The following are examples of regulatory drawbacks:

- the alternative designs proposed in the license application may generate controversy about when construction would be considered substantially complete; and
- if the licensing process freezes the repository design and its safety case, the implementer cannot further develop this design during the regulatory review process. If new information warrants a change to the reference design, the implementer must then request a license revision, which could extend significantly the review schedule.

4.10.2 Regulatory advantages

Adaptive Staging also has several regulatory advantages (e.g., NRC, 2001):

- It may bring additional information to the regulator about the strengths and weaknesses in the safety case, thereby allowing the regulator to make decisions on the basis of better evidence.
- As stated in regulatory documents from many countries (USNRC, 1998; EPA, 1999; HSK/KSA, 1993), proof that the proposed geologic repository meets any specific set of regulatory standards cannot be demonstrated in the ordinary sense of that word. In Adaptive Staging, this fact is accepted and communicated to regulators, implementers, stakeholders, and the general public. In turn, these parties can help identify additional uncertainties and suggest ways to address them. In this context, Adaptive Staging may provide additional confidence to stakeholders.
- The openness inherent in Adaptive Staging may increase public trust in the regulator and by extension in the repository program. The regulatory body's ability to adopt and utilize a less prescriptive system that involves more judgment is tied to the degree of trust that body enjoys with the broad public. The more trust, the more deference is afforded the regulatory body to exercise judgment instead of relying on prescriptive "yes or no" findings, and the more likely is public acceptance of the regulator's decisions.

4.11 Impact on the institutional and societal context

Adaptive Staging has the following impacts on the institutional and societal context:

- opportunities for societal and institutional learning;
- opportunities to increase trust in the implementing institution; and
- opportunities to test mechanisms for stakeholder and public involvement.

A change of the implementer's organizational culture may be required to implement Adaptive Staging in the repository program. Learning will be minimal unless the implementer actively seeks out alternative viewpoints, openly acknowledges errors and uncertainties, specifically addresses societal issues, and organizes and undertakes relevant research to improve the knowledge base. In recent decades, managers of large-scale technological systems have often encountered societal and political resistance, which generates gridlock. The management of nuclear waste is an example of technology gridlock. No country has achieved a satisfactory solution to the disposal of high-level waste, despite considerable and costly efforts (NRC, 2001; Rosa and Clark, 1999). However, sustained progress in some countries provides indications that programs may succeed.

One cause of gridlock is lack of public trust. Public acceptance of the choice for disposal of high-level nuclear waste depends on trust in the implementer and the regulator. Lack of trust is, in part, a result of the gap in technological understanding between scientists and lay people. One of the challenges to implementers and regulators is the inherent asymmetry in trust.

4.11.1 Mechanisms for stakeholder involvement

Stakeholder input to the decision-making process is of paramount importance for effective implementation of Adaptive Staging. Adaptive Staging encourages and explicitly calls for interaction with stakeholders and the general public at Decision Points (see Figures 2.1a, b, and c). The 1996 National Research Council report, *Understanding Risk,* concluded that active public participation from the outset and throughout the decision-making process is essential to managing risks (NRC, 1996). That report makes explicit the delineation of the relationship between analysis and deliberation and the central role played by interested and affected parties. Adaptive Staging's Decision Points have elements in common with the deliberative-analytic process described in the 1996 report. The same report also discusses challenges of including stakeholders in the decision-making process.

This challenge is summarized in the recommendation to "get the right participation and get the participation right." Getting the right participation means that the decision-making process should have sufficiently broad participation to ensure that important, decision-relevant information enters the process, that all important perspectives are considered, and that the parties' legitimate concerns about inclusiveness and openness are met. Getting the participation right means that the decision-making process should satisfy most parties, including stakeholders, that it is responsive to their needs; that their information, viewpoints, and concerns have been adequately presented and taken into account; that parties have been adequately consulted; and that their participation has been able to affect the way risk problems are defined and understood (NRC, 1996; p. 7).

The need for public confidence to achieve successful implementation of radioactive waste management is also recognized by the International Association for the Environmentally Safe Disposal of Radioactive Materials (EDRAM):

"There seems to be a widespread awareness among EDRAM members that greater public confidence is needed for the successful implementation of radwaste [radioactive waste] management. The stepwise approach has been adopted to varying degrees, and there is a growing awareness that it will facilitate the work involved in gaining public confidence ...
Most of the EDRAM countries share an emphasis on the need for public acceptance of the radwaste management system, and different methods are suggested for creating public confidence:

- good relations with the public,
- creation of local partnership with different stakeholders at local level,
- transparency in the decision-making process,
- public review of documents and plans,
- distribution of materials to all parties and the creation of information strategies,
- local information offices at feasibility study sites and site tours,
- changes in internal organisation to make openness the key concept for all employees,
- feedback mechanisms for every phase of the process,
- issue-specific voting and the creation of ad-hoc groups for discussion,
- stepwise and flexible approach involving discrete and explicit implementation steps,
- progressivity and reversibility of the implementation process,
- retrievability of the waste,
- postponed final decisions, which means that there is ample opportunity for knowledge dissemination, discussion, and reflection" (EDRAM, 2002; pp. 13-14).

The above list bears many similarities to Adaptive Staging. Adaptive Staging can address the issue of public acceptance because of its cautious approach, its structured flexibility, its scheduled periods for reflection and decision-making, and its openness to assimilating all relevant data—including societal and political data. Specifically, Adaptive Staging's attributes of flexibility, transparency, auditability, and responsiveness provide a set of principles and a mechanism for interactive, iterative stakeholder involvement.

The committee is not in a position to specify the appropriate "mechanisms" ensuring effective stakeholder and general public participation. Adaptive Staging provides opportunities to test the effectiveness of possible methods for stakeholder involvement. The committee suggests that a stakeholder advisory board be formed and a research program formulated for determining the optimum mechanism for public participation (see Sidebar 4.2).

The committee acknowledges that changing methods of stakeholder and/or general public involvement can undermine the implementer's or regulator's reputation for constancy and consistency. Parties who are not already involved in the program are an important audience for an organization's behavior. It is especially difficult to educate this more distant audience about the experimental character of an organization's behavior. Therefore, social science work needs to be an integral component of the overall process of developing a successful repository program. In parallel with engineering activities and throughout the program phases, social science work is also included in Adaptive Staging.

Adaptive Staging addresses the challenge of public concern and controversy by providing opportunities for the implementer to demonstrate competence and integrity. Adaptive Staging can also provide additional opportunities to build public trust in the capabilities of the implementing institution to fulfill very long-term responsibilities. Finally, Adaptive Staging's commitment to systematic learning in the social sciences recognizes directly that implementing a repository presents both societal and technical challenges.

It is impossible to foresee the outcome of Adaptive Staging on public concerns, any opposition, or controversy. The following are examples of possible negative outcomes:

1. Adaptive Staging may be perceived as self-serving. That is, stakeholders may perceive Adaptive Staging as a stratagem to develop a specific site or to begin waste emplacement prematurely, thus decreasing trust.
2. Experimentation with mechanisms of stakeholder involvement may undermine public trust by showing the implementer to be an organization that lacks constancy.
3. Adaptive Staging provides stakeholders opposed to the repository program additional opportunities to deliberately delay the program (with obstructions at Decision Points).
4. Public trust in the institution may never be achieved, even if adaptable staging is implemented, especially if there already exists a climate of institutional distrust.

4.12 Summary of potential benefits and drawbacks of Adaptive Staging

Do the benefits of Adaptive Staging outweigh the potential drawbacks for the implementer? Potential benefits and drawbacks of Adaptive Staging compared to Linear Staging are summarized below.

4.12.1 Potential Benefits of Adaptive Staging

The committee's position in favor of Adaptive Staging is based upon the following considerations:

- **Programmatic:** Adaptive Staging is a logical approach for managing complicated projects. When the project is divided into smaller stages with the possibility of reversal, the decision-making process can become more manageable. Adaptive Staging allows decision-making only on those stages of repository development where knowledge is available (near-term stages), thus keeping options open for the future. Its flexibility attribute could help the implementer react to unavoidable "technical surprises" and unavoidable political, economic, or societal surprises. Its incremental nature could also help the implementer identify problems early, problems that may become difficult to rectify at later stages. It also allocates sufficient effort and time for quantification and analysis of the relative risks of different options.

- **Technical:** Adaptive Staging allows for learning and incorporating new technical data not only throughout repository development, but also after the waste is in place. For instance, it encourages the implementer to develop long-term monitoring and science and technology programs. Data from these long-term programs could improve scientific and engineering understanding of the repository system behavior.
- **Regulatory:** Because of Adaptive Staging's increased number of transparent, auditable Decision Points, regulators are able to evaluate the program more often. Adaptive staging provides the regulator with better oversight of the repository design, operations, and safety.
- **Institutional:** Adaptive Staging could help build public trust in the capabilities of the implementing institution to fulfill very long-term responsibilities because it allows many opportunities for the implementer to demonstrate competence and integrity.
- **Societal:** Allowing stakeholder participation in the decision-making process can make the repository program more credible and trustworthy. Previous National Research Council committees have discussed the benefits of broad public participation in governmental agencies' decision-making processes (NRC, 1994, 1996, 2001).

4.12.2 Potential Drawbacks of Adaptive Staging

The committee also has identified potential programmatic, technical, regulatory, institutional, and societal drawbacks of Adaptive Staging:

- **Programmatic:** Adaptive Staging calls for financial investments without a "guarantee" that any of the potential future stages in the process will be reached. Adaptive Staging may also extend the time scale needed for full-scale operation of the repository, thereby changing surface buffer storage requirements and other factors, such as costs. Adaptive Staging may also encourage funding organizations to release funding only in limited allocations that can make the implementer's planning more difficult.
- **Technical:** Adaptive Staging may lead to longer periods in which the waste is more accessible to humans. If the time scales become very long (centuries) then institutional stability cannot be guaranteed. In this case, workers could be exposed to higher doses of radiation and security concerns could increase.
- **Regulatory:** More intensive regulatory oversight may delay the repository program. Moreover, Adaptive Staging requires flexibility and acceptance of the regulatory risks involved in permitting or licensing individual stages in an open-ended program.
- **Institutional:** Stakeholders may perceive Adaptive Staging as a stratagem to develop a specific site or to begin waste emplacement prematurely, thus decreasing trust. Public trust in the institution may never be achieved, even if Adaptive Staging is implemented, especially if there already exists a climate of institutional distrust. Adaptive Staging may require changes in the culture and management practices of the implementer that may be difficult to achieve in practice.
- **Societal:** Implementers are often strongly technically oriented; therefore, commitment to social science research and to the development of effective

mechanisms of public participation may require efforts by both the implementer and stakeholders. Stakeholders opposed to the repository project may have additional opportunities to deliberately delay (physically or legally) the program.

On balance, the committee judges that the potential advantages of Adaptive Staging outweigh these potential drawbacks. As noted in Section 1.2, the committee believes that the features of Adaptive Staging (e.g., its attributes and Decision Points) can address the technical and societal challenges of a geologic repository program. This belief is based on the committee's knowledge of repository programs worldwide, its comparisons with other complex projects, and its perception of the compatibility of Adaptive Staging with the principles of sound project management. The inherently self-correcting nature of Adaptive Staging reduces the risk of using such an approach. Given the limited successes of Linear Staging, and given Adaptive Staging's use of multiple Decision Points for addressing Linear Staging's limitations, the committee judges that a successful repository program is more likely with Adaptive Staging.

5

Specific Applications to the Yucca Mountain Project

This chapter contains the committee's observations on application of Adaptive Staging to the U.S. repository program and the committee's assessment of the current Department of Energy (DOE) approach to staging. To develop specific and constructive advice, this chapter follows a different approach from the generic Chapter 4 by identifying the main challenges DOE is facing in the immediate future and discussing how these might be addressed with Adaptive Staging.

The Nuclear Waste Policy Act (NWPA) of 1982 established a framework for implementing a geologic repository for high-level waste in the United States (NWPA, 1982). The U.S. repository program for high-level waste, proposed for Yucca Mountain, Nevada, is now entering the licensing phase. DOE has set (and revised) a roadmap for completion of the repository program (DOE-OCRWM, 2001b) according to the schedule established in the NWPA and its amendments. Figure 5.1 shows the current (as of January 2003) milestones (see also Appendix F). Several major events took place during this study: in 2002, DOE submitted the site suitability recommendation to the President, the President recommended the site to Congress, the State of Nevada vetoed the recommendation, and Congress over-rode Nevada's veto and authorized DOE to apply for a license to construct the repository at Yucca Mountain. Section 5.3 lists the challenges presently facing DOE and Section 5.4 describes how Adaptive Staging could address these challenges. Further information on the Yucca Mountain project is provided in Appendix F and references therein.

5.1 Impacts of Adaptive Staging on the U.S. repository program

Impacts of Adaptive Staging on a generic repository program are given in Chapter 4 while specific impacts on the Yucca Mountain Project are in the following section.

5.1.1 Licensing

Chapter 4 addressed in general the impacts that Adaptive Staging can have on the licensing phase (Section 4.2.1) and on the regulatory framework (Section 4.10). One U.S.-specific impact is that much greater emphasis would be placed on the formulation and periodic evaluation of a safety case, as defined in Sidebar 2.1, and tailored to the Yucca Mountain project in Sidebar 5.1. The U.S. regulations require DOE to submit a safety analysis but not a safety case. The technical content is, however, equivalent (see Sidebar 5.1). Although the regulation does not use the term safety case, the USNRC Yucca Mountain Review Plan reads:

SIDEBAR 5.1 DOE's Safety Case for Yucca Mountain

The committee uses the term "safety case" in the broad sense described in Sidebar 2.1, that is, a collection of arguments reassessed at given stages of repository development in support of the safety of the repository. The committee believes that the Department of Energy (DOE), as the repository implementer, should develop the broad safety case, as described in Section 2.1, for guiding its safety work and explaining its safety arguments. To see how this conforms to the licensing requirements in the United States, it is necessary to look at the terminology and procedures defined by the Nuclear Regulatory Commission (USNRC) regulations.

The term safety case is not used by the USNRC for the analysis of post-closure safety, which is of greatest relevance here. The applicant (DOE) is required to submit a complete application and an environmental impact statement that are sufficient for the USNRC to make a determination of safety for the repository, including "reasonable expectation that the materials can be disposed of without unreasonable risk to the health and safety of the public" (10 CFR Part 63.31). A central element of the complete application is to be a performance assessment. *Performance assessment* (definition from 10 CFR 63.2) means an analysis that:

> "(1) Identifies the features, events, processes (except human intrusion), and sequences of events and processes (except human intrusion) that might affect the Yucca Mountain disposal system and their probabilities of occurring during 10,000 years after disposal;
>
> (2) Examines the effects of those features, events, processes, and sequences of events and processes upon the performance of the Yucca Mountain disposal system; and
>
> (3) Estimates the dose incurred by the reasonably maximally exposed individual, including the associated uncertainties, as a result of releases caused by all significant features, events, processes, and sequences of events and processes, weighted by their probability of occurrence" (66 Federal Register 55794, November 2, 2001).

Specific requirements for the performance assessment are also described in the regulations (see 10 CFR 63.114) and these are broadly similar to the safety case concept described by the committee. The USNRC stipulates that the performance assessment must:

> "[...] (b) Account for uncertainties and variabilities in parameter values and provide for the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment.
>
> (c) Consider alternative conceptual models of features and processes that are consistent with available data and current scientific understanding and evaluate the effects that alternative conceptual models have on the performance of the geologic repository. [...]

(e) Provide the technical basis for either inclusion or exclusion of specific features, events, and processes in the performance assessment....

(f) Provide the technical basis for either inclusion or exclusion of degradation, deterioration, or alteration processes of engineered barriers in the performance assessment, including those processes that would adversely affect the performance of natural barriers....

(g) Provide the technical basis for models used in the performance assessment such as comparisons made with outputs of detailed process-level models and/or empirical observations (e.g., laboratory testing, field investigations, and natural analogs)" (66 Federal Register 55807, November 2, 2001).

In its performance assessment analyses, DOE regularly presents estimates of radiation exposures that peak long after the 10,000-year term of regulatory compliance. The USNRC does not indicate whether it will consider or evaluate results beyond the 10,000-year compliance term, but the USNRC does require the DOE application to be accompanied by the environmental impact statement that presents and evaluates these results.[a] In response to concerns that performance assessments would be relied upon as the sole quantitative technique for evaluating compliance the USNRC stated:

"Although repository post-closure performance is evaluated with respect to a single performance measure for individual protection, the NRC considers a broad range of information in arriving at a licensing decision. In the case of the proposed repository at Yucca Mountain, Part 63 contains a number of requirements (e.g., qualitative requirements for data and other information, the consideration and treatment of uncertainties, the demonstration of multiple barriers, performance confirmation program, and QA program) designed to increase confidence that the post-closure performance objective is satisfied. The Commission will rely on the performance assessment as well as these other requirements in making a decision ..." (66 Federal Register 55746, November 2, 2001).

When comparing these requirements with the characteristics of the safety case, the technical content appears to be equivalent. The primary differences are that the safety case presents key safety arguments understandably by a wider audience and it is updated more often.

[a]The EPA regulation, 40 CFR Part 197.35, requires DOE to include the "results and their bases in the environmental impact statement for Yucca Mountain as an indicator of long-term disposal system performance."

"The [USNRC] staff will decide which [model] abstractions are important to performance, by using risk insights gained from performance assessments, knowledge of site characteristics and repository design, and review of the U.S. Department of Energy safety case" (USNRC, 2002, Section 4.2.1.3, pp. 4.2-16)

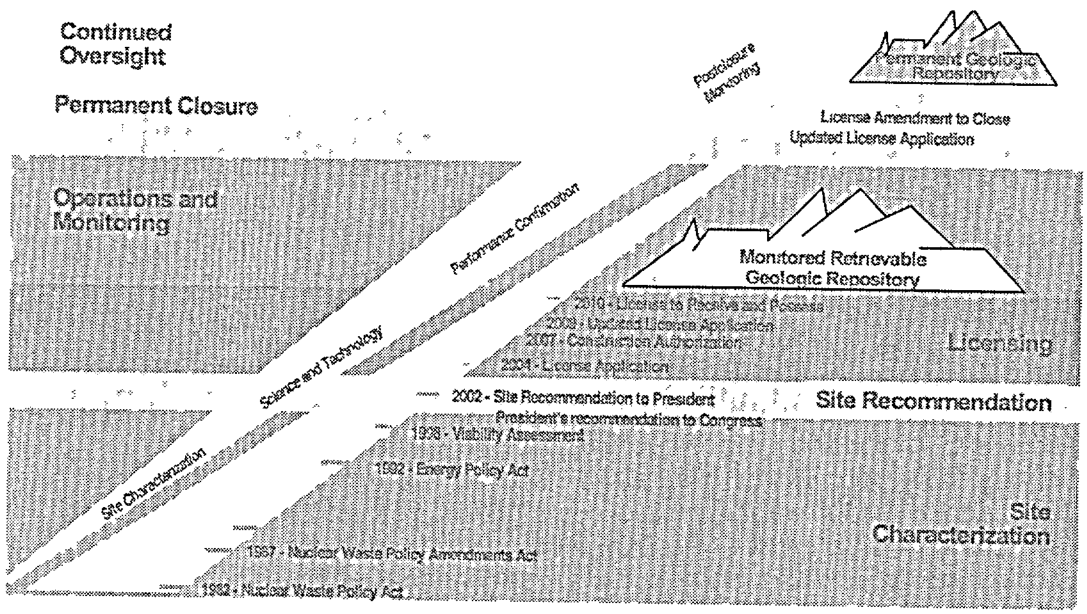

FIGURE 5.1 Major milestones in the U.S. approach to a high-level waste geologic repository. In 2002, Nevada vetoed the site recommendation but Congress over-rode the veto and authorized DOE to apply for a license to construct the repository at Yucca Mountain (not shown). SOURCE: Williams, 2002.

The USNRC Center for Nuclear Waste Regulatory Analyses also recently published an article on the importance of transparency and traceability in building a safety case for high-level waste repositories (Mohanty and Sagar, 2002).

At each Decision Point, new information is evaluated and used to update the safety case, if necessary. Then this updated safety case together with all relevant information are used to decide how to proceed (i.e., whether to proceed on the original course or revise the course of action in the reference framework). The committee does not imply that the safety case should be an additional USNRC licensing requirement or that the regulations are inadequate to evaluate repository safety.

Some Decision Points for DOE correspond to the decisions to apply for licenses (i.e., the next license for whatever point the program currently finds itself). DOE is responsible for the license application but the actual decision to issue a license is made by the USNRC.

DOE has so far attempted to describe a safety case for Yucca Mountain in the iterative series of documents called "Repository Safety Strategy." To date, DOE has issued four versions of the safety strategy for a Yucca Mountain repository. The OECD/NEA and IAEA jointly reviewed revision 3 of DOE's safety strategy and concluded that:

> "[revision 3] is a first commendable attempt at outlining the strategy for achieving safety and for demonstrating compliance with the regulations as well as the basis for confidence in the analyses. The [review team] suggests that the information contained in [revision 3] should be updated and extended, and used as a basis for developing the proposed safety case document for the next phase of the programme" (NEA, 2002, p. 58).

The IAEA recently recommended that further work be undertaken for "establishing generally the content of a safety case" (IAEA, 2001b, attachment 1, p. 2). The joint NEA-IAEA International Peer Review of the Yucca Mountain Site Characterization Project's Total System Performance Assessment recommended "A safety case report should be developed along the lines discussed in the NEA confidence document" (NEA, 2001a, Section 5.3; Recommendations for Future Assessements). The committee agrees with this recommendation. DOE expressed to the committee and to the Nuclear Waste Technical Review Board its commitment to pursue its efforts in preparing a safety case (Van Luik, 2001; Ziegler, 2002).

Another impact of Adaptive Staging on the first (construction) license application is that the implementer and regulator must both be clear about the possibility of, and mechanisms for, implementing Adaptive Staging. It is important that both organizations recognize and distinguish those DOE actions, such as changes in the reference design, tests, or experiments, that require USNRC approval in advance, and those that can be made without advance approval. The USNRC has already identified and provided decision criteria for some changes, tests, and experiments that can be made without advance regulatory approval in 10 CFR Part 63.44(b)(1). The first construction authorization application with Adaptive Staging would explicitly address this distinction.

DOE could choose in its first application for a construction authorization to propose a pilot stage of the reference design. The license application would be based on the full safety analysis for 70,000 metric tons of heavy metal (MTHM[1]).

The application might seek an initial license to construct a non-radioactive pilot facility for the purpose of learning about waste emplacement, retrieval, and other operational details. Subsequently, this non-radioactive pilot could become a radioactive pilot and a demonstration facility when the license to emplace waste is obtained. The application would likely include at least some key surface facilities including buffer storage.

5.1.2 Construction

DOE's initial plan was to construct the entire repository continuously while applying for the license to receive and emplace waste after a substantial part was constructed. The current plan is to adopt a "modular design" in which the surface and subsurface facilities are built as discrete segments or "panels" (DOE-OCRWM, 2002a,b). An example of the impact of Adaptive Staging on the initial application for construction authorization concerns the selection of the thermal operating mode in the repository. In an Adaptively Staged program, the final thermal operating mode for the repository might be determined after pilot and tests activities have provided preliminary *in situ* results.

The initial construction stage could provide data concerning repository building and testing with non-radioactive simulated waste. Emplacement mockups demonstrating the retrievability mentioned above could be included in this stage as well as the testing and demonstration of surface packaging and welding facilities.

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[1]Section 114(d) of the Amendment to the NWPA limits the capacity of the repository to 70,000 MTHM. Current DOE plans project that about 90 percent (by mass) would be commercial spent nuclear fuel; and 10 percent would be defense high-level waste. Most programs use the MTHM as mass unit because it roughly corresponds to the mass of nuclear fuel, everything else being lighter than the heavy metals.

These activities could be defined in the license application. The committee understands that the choice of transportation corridors to Yucca Mountain and the implementation of transport systems are not a direct part of repository licensing, but that DOE would be expected to plan them during this stage.

5.1.3 Operations

Before beginning operations, DOE must receive the USNRC license to receive and emplace waste. The license authorizes DOE to take title to high-level waste stored at generator sites, transport it, and emplace it in the repository. During the lengthy period from initial waste emplacement to repository closure, the monitoring and performance confirmation programs, initiated during site characterization, will continue. The USNRC requires waste retrievability throughout the period when wastes are being emplaced and for 50 years after emplacement. The current repository design allows the repository to remain open for up to 300 years, a period acceptable under the regulations. The issue of waste retrievability is part of the larger topic of reversibility. DOE's current program is consistent with Adaptive Staging in that it maintains reversibility throughout the program (i.e., beyond the 50-year requirement).

As mentioned in Chapter 4, Adaptive Staging during the operational phase implies the implementation of test and pilot activities before increasing the emplacement rate to full-scale operation (Section 4.2.2).[2] After the license to emplace the waste is obtained, an initial amount of waste could be emplaced in an initial panel. This facility could be heavily instrumented and would serve as a pilot facility to confirm or modify the design or operations. If the design is not changed as a result of pilot operations, the same area could also continue as a demonstration site during and after repository operations. Otherwise, a dedicated area elsewhere could be chosen to serve as a long-term demonstration of the final implementation configuration. Using this initial panel, not as a module of a fixed design but as a pilot facility, could maximize the knowledge gained in the early operational phase to affirm or improve the repository design. Examples of the types of activities and tests for the pilot stage might include:

- movement of wastes from the surface to the subsurface, while ensuring all aspects of worker safety;
- demonstration of emplacement and retrieval of waste packages in the presence of drip shields, using both simulated and actual radioactive waste;
- analysis of worker exposure to radiation and industrial accident risk when handling, packaging, and emplacing waste using associated equipment;
- analysis of barriers to develop a good safety culture;
- monitoring the engineered barriers and adjacent natural systems in great detail;
- installing backfill material as would be carried out in preparation for repository closure; and
- demonstrating retrievability.

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[2]As previously mentioned, pilot and test activities are consistent with good engineering practices and are not exclusive to Adaptive Staging.

A test facility should be designed to answer or resolve critical design and scientific questions. A test facility can be operated from the initial licensing phase through the operational phase for as long as open questions on system behavior need to be addressed. This period could include such aspects as testing: (1) different thermal operating modes; (2) alternative drip shield materials, designs, and construction and emplacement methods; (3) alternative backfill materials; and (4) alternative and innovative monitoring methodologies.

There are other types of learning activities beyond tests performed in an underground facility, such as: (1) assessing public, affected communities, and stakeholder (see Sidebar 5.2) attitudes; (2) testing for improved public involvement; (3) evaluating mechanisms to improve the safety culture (see Section 2.2); (4) implementing methods for incorporating input into key decisions; and (5) improving implementer's and regulator's involvement in learning activities.

Pilot stage activities are selected based on their importance for the safety case and the operational effectiveness of the repository system. For example, DOE's performance assessment for the repository relies heavily on the performance of the titanium drip shield. Therefore, it is important to test this component and alternatives during the pilot stage. The committee acknowledges that pilot operations cannot provide information on the long-term behavior of the drip shield. However, the pilot-scale activities can provide operational experience or demonstrate the need for alternatives that may reduce overall cost and improve performance. Considering the mechanical complexity of emplacement and retrieval of the waste packages, drip shields, and possible backfill, DOE could plan an early demonstration, at least with mockups, of these critical steps as part of the preclosure safety analysis.

As a part of the pilot operation or as a special test, a demonstration of retrieval should provide proof of the implementer's capability to retrieve waste from Yucca Mountain. Such demonstration should be transparent to stakeholders, the USNRC, and other oversight groups, such as the Nuclear Waste Technical Review Board[3] (NWTRB).

In Adaptive Staging, several advisory and consultative processes are seen to provide direct input to the program (see Section 4.2). For example, DOE could establish a technical oversight group, independent of the federal government, that would interact with the State of Nevada to provide input into the repository program.[4] There could also be a stakeholder advisory board that could ensure consultation with stakeholders and the general public at each Decision Point. These oversight groups would not overlap with the NWTRB: they would be separate entities mainly because they are involved with the State of Nevada and they would be actively involved in DOE's decision-making process (although final responsibility rests with DOE).

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[3]Congress created NWTRB in 1987 to review DOE's scientific and technical activities pertaining to the management and disposal of the nation's commercial spent nuclear fuel. Board members are appointed by the President of the United States. Additional information on the NWTRB can be found on the Internet at <http://www.nwtrb.gov>.

[4]For example, in New Mexico the Environmental Evaluation Group (EEG) is the independent technical oversight group for the Waste Isolation Pilot Plant. More information on the role of EEG is provided in Sidebar F.1, Appendix F.

5.1.4 Closure and post-closure

As noted previously, the U.S. program contemplates an operational phase of about 50 years and a monitoring period lasting 50 years following the operational phase (66 Federal Register 55738, November 2, 2001). Section 4.2.3 describes the impacts of Adaptive Staging on closure and post-closure phases. Given these long time frames, it is premature to speculate in detail on the specific impacts of Adaptive Staging on closure and post-closure in the U.S. program. Monitoring performed throughout the operational phase can be extended for as long as society deems necessary (pending technology), and adaptations, up to reversal, remain feasible far into the future.

Sidebar 5.2 Stakeholders in the U.S. Program

The DOE, consistent with the broad interpretation of stakeholder outlined in Chapter 3 (Sidebar 3.2), defines stakeholder to include any person or organization with an interest in, or who is affected by, the decisions of the implementer of a nuclear repository. This includes representatives from federal, state, tribal, and local agencies; members of Congress or state legislatures; unions, educational groups, environmental groups, and industrial groups; and members of the general public (DOE-OCRWM, 2002a).

This definition covers the widest range of potential participants in the decision process, thereby reducing the chances of disenfranchising any legitimate stakeholder. Included among the federal agencies in the DOE definition are the implementer and the regulators. As pointed out in Sidebar 3.2, this definition has operational disadvantages because it neglects to distinguish stakeholders who have a codified, institutional, and continuous status, such as Congress, the implementer, and the regulators, from individuals and groups whose standing is neither codified nor permanent and whose stake is more issue-specific. It also fails to distinguish active stakeholders from passive members of the general public. DOE's definition, therefore, contains ambiguities that dilute its precision and constrain its application.

To avoid these ambiguities the committee has distinguished three categories of stakeholders: institutional stakeholders, stakeholders, and the general public. With respect to Yucca Mountain, the implementer and regulators—institutional stakeholders—are identified by their titles (i.e., as DOE, USNRC, and the U.S. Environmental Protection Agency, the State of Nevada, and local governments). The term "stakeholder," consistent with typical usage of the term, refers to individuals, groups, and organizations that have an active interest and become engaged in the siting and management decisions in connection with the Yucca Mountain repository. The "general public" in this committee's report is all other citizens who may have a stake in the siting and management decisions of the Yucca Mountain repository but who remain as spectators unengaged in the decision process.

5.2 Committee's assessment of the U.S. approach to staging

DOE recognized early that there are advantages in staging a repository development program; hence its request to National Research Council to perform the present study. Some of the attributes stressed by the committee as essential for Adaptive Staging are incorporated into the U.S. program; for example, stakeholders have access to a great amount of documentation and information.[5] DOE has also been introducing other characteristics of Adaptive Staging into its program, the obvious examples being the increased emphasis on a potential pilot stage (see Appendix F, Section F.1.4), development of a safety case approach (see Section 5.1.1), and demonstration of the feasibility of waste retrieval (see Section 5.1.3).

DOE has not incorporated all attributes simultaneously, and therefore its approach remains essentially Linear (see Figure 5.1 and Section F.2 in Appendix F). This linearity is illustrated by the recurring tendency to propose unrealistically tight program schedules and by the lack of transparency in some decision processes. The major milestones in Figure 5.1 are, of course, important decisions, but these are not Decision Points because these milestones correspond mainly to regulatory licensing decisions. Adaptive Staging envisions many more Decision Points than decisions to apply for licenses. For example, there may be a long period of operations between receipt of the license to receive and emplace waste and pre-closure activities. This time period would be divided into several work stages of appropriate duration—a small number of years for each—separated by Decision Points, at which DOE would then evaluate new knowledge gained from operational experience, monitoring and research, and other information. With all of this information, DOE would update the safety case, as needed, and decide how to proceed.

As mentioned in Section 2.4, Adaptive Staging does not require program "stops" at each Decision Point. A Decision Point can be conducted in parallel with program operations. Decision Points can be folded into the schedule so that, if a problem arises, it can be addressed without disrupting the entire program.

An example of Linear approach in DOE's current program is its view that reversibility is guaranteed because Congress can direct the abandonment of the Yucca Mountain site (Williams, 2002). The committee concludes that reversibility is not an inherent attribute of the DOE program; rather, DOE considers reversibility as something externally imposed. DOE has not, to date, demonstrated a commitment to transparency in its decision-making. For example, the decisions to adopt the titanium drip shield and to select C-22 alloy for the container occurred suddenly and with little external discussion. Further examples of Linearity in DOE's approach are in given in Appendix F.

5.3 Challenges facing the U.S. repository program

Like all national repository programs, the U.S. repository program must be implemented in a country-specific legal, institutional, and societal context. This context is shaped by several factors, including the following:

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[5]Some have argued that stakeholders are buried under excessive information, making the understanding and the interpretation of data difficult.

- environmental laws and regulations, in particular, the Nuclear Waste Policy Act and its amendments;
- legal suits between DOE and utility companies affecting waste shipment schedules;
- legal suits between the State of Nevada, DOE, and other federal agencies; and
- the attitude of the stakeholders and the general public toward the U.S. nuclear waste program and the Yucca Mountain Project, in particular.

Following Congress' approval for DOE to move to the license application phase, DOE is currently facing the following major challenges:[6]

- finalizing repository design and operational strategies for the license application;
- obtaining a license to construct the repository and emplace waste;
- planning for interim or buffer storage requirements;
- constructing the repository and beginning operations under current schedules and budgets;
- designing and implementing a transportation plan;
- working to maintain or enhance scientific and institutional credibility;
- working to maintain effective working relationships with the nuclear power utility companies who possess the spent fuel to be disposed of at Yucca Mountain; and
- improving working relationships with stakeholders and the general public.

The committee discusses below how Adaptive Staging is a possible approach to enhance the chances of successfully addressing these challenges. The committee acknowledges that Adaptive Staging is not the only management approach that can address these challenges and recognizes that other project management approaches have many features in common with Adaptive Staging. Moreover, because Adaptive Staging is untested, there is no guarantee that adaptive changes will have a positive impact on the DOE program. Nevertheless, as discussed in Chapter 4, the committee believes this approach is promising. It is important to recognize that, to be effective, all of the attributes of Adaptive Staging must be adhered to, not just a selected few. Satisfying a given attribute may be necessary but not sufficient to address the challenge in question.

5.4 Addressing these challenges

The committee believes that there are substantial opportunities for DOE to implement Adaptive Staging in the current program. The sooner Adaptive Staging is adopted, the more effective it likely will be.

[6]These challenges were formulated on the basis of the committee's expertise and through discussion with DOE representatives. Challenges are not presented in a priority order.

5.4.1 Finalizing repository design and operational strategies for the license application

Adaptive Staging could introduce more flexibility and learning opportunities into the licensed design and operating mode (see Sections 2.1.2 and 4.2). An Adaptive Staging approach recognizes that design changes may occur during the operational phase but that a robust and safe design is needed for licensing. To allow for this flexibility it is important that the implementer and regulator discuss how design (and other) changes can be incorporated in the licensing process (see Section 5.4.2).

If the licensing process were to acknowledge the commitment to systematic learning (i.e., a search for effective opportunities for improvement throughout the repository program), later changes to the program would not come unexpectedly. For instance, DOE could justify in a transparent manner a decision to postpone the selection of the thermal operating mode until more evidence has been gathered and alternatives have been evaluated through test and pilot activities.

Introducing a pilot stage and a test facility is an example of how an Adaptive Staging approach can address the challenge of completing the design and operational details of the Yucca Mountain repository. The initial pilot and test facilities could test with non-radioactive waste various alternatives for waste configuration, waste packages, backfills, and thermal operating modes in repository management. Operational information gathered during the pilot stage with non-radioactive waste[7] can be used to complete the design and can be presented in the license application to support the choice of design and operational details.

Adaptive Staging requires analysis of waste storage and underground emplacement requirements, as well as consideration of thermal operating modes as a function of shipping rates. This analysis is particularly important because the thermal and radiological properties of the various types of waste coming to Yucca Mountain (i.e., commercial spent nuclear fuel, DOE spent fuel, naval reactor fuel, and defense high-level waste) may affect repository design and stages. Generally, the radioactivity and heat load of commercial spent nuclear fuel is substantially higher than that for defense high-level waste and naval spent fuel. Spent naval fuel is less proliferation-resistant because of its highly enriched uranium content. Defense high-level waste is low in plutonium content.

Before proceeding to full-scale operations, the results of pilot operations and of ongoing tests should be thoroughly examined to determine the optimum method to develop the remainder of the repository. Although results from the pilot stage may not cause major changes in the operational plan, planning for the final design, surface and underground, should be sufficiently flexible to incorporate improvements that may become apparent in the future. Major changes in design should be subject to USNRC review. For those modifications that address issues of public concern and debate, the structured decision-making process would give DOE the opportunity to engage stakeholders in a discussion of the proposed changes. Issues requiring public debate may be identified by DOE, the technical oversight groups, or the stakeholder advisory board. Adaptive Staging also encourages examination of all options available for scheduling the emplacement of different waste types with different characteristics (commercial spent nuclear fuel, naval reactor fuel, and defense high-level waste) in the repository.

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[7]The pilot stage using radioactive material must be part of the license application as an operational activity.

Public acceptance of defense-related waste disposal in the repository might differ from commercial spent fuel disposal. Naval fuel management also involves consideration of broader national security interests. DOE could consider whether the difference in public acceptance is an important factor, along with utilities' concerns, in prioritizing shipment of different waste streams to the repository.

Adaptive Staging would also stress the importance of enhancing the safety culture (Section 4.8) in the repository program. The safety-culture mentality that has long been promoted in nuclear circles can also be complemented within the institution by an environmental culture that is now finding expression in official ISO standards. The ISO 14001 certification (Section 4.8) could be a vehicle for focusing the attention of DOE and its contractors on safety and environmental issues and could promote public trust by meeting a known and independently accepted standard for environmentally responsible management. ISO 14001 has been successfully implemented at DOE's geologic disposal facility for transuranic waste at the Waste Isolation Pilot Plant. Other applications of ISO 14001 in the United States are discussed in the National Research Council report *Environmental Management Systems and ISO 14001* (NRC, 1999). The goal of a safe and efficient repository can be reached only if this safety culture permeates the entire organization, including management and contractors.

5.4.2 Obtaining a license to construct the repository and to emplace waste

Licensing poses many challenges for DOE and the USNRC that could be addressed using Adaptive Staging. However, Adaptive Staging cannot be effective if it is not implemented at the beginning of the licensing process to determine, as mentioned earlier, how design (and other) changes will be handled in the licensing process. Key features of the licensing process are spelled out in statutes, regulations, guidance documents, and other USNRC position statements. DOE has lead responsibility as the implementer to make the complete safety analysis demonstrating that the repository design is conservative and effective, that the repository site is suitable, and that there is compliance with all regulatory requirements. Demonstration of compliance with the regulator's numerical requirements does not by itself constitute a safety case as understood by the committee. For example, DOE's assessment of repository performance beyond the 10,000-year regulatory compliance term could be addressed in the safety case even though it is not required by the USNRC. The three main challenges in the Yucca Mountain repository licensing process are (1) ensuring completeness of the application; (2) making and maintaining the safety analysis; and (3) choosing licensing stages within the current regulatory framework.

- **Ensuring completeness of the application.** The primary responsibility for any applicant is the demonstration of safety. The underlying regulatory philosophy used by the USNRC in fulfilling its regulatory mission can be found in the USNRC Strategic Plan and is restated in the Yucca Mountain Review Plan (USNRC, 2000). It embodies the principle that the licensee is responsible for the safe operation of a nuclear facility: "the burden of proof is on the applicant or the licensee to show that the proposed action is safe, to demonstrate that regulations are met, and to ensure continued compliance with the regulations" (see Sidebar 5.3). The application must also show that the proposal fully complies with all regulatory requirements.

Sidebar 5.3 The Nuclear Regulatory Commission Licensing Review Philosophy

The following is a quotation from the Nuclear Regulatory Commission's Yucca Mountain Review Plan illustrating the licensing review philosophy:

"The following three principles are important in implementing the U.S. Nuclear Regulatory Commission regulatory mission:

- The U.S. Nuclear Regulatory Commission does not select sites or designs, or participate with licensees or applicants in selecting proposed sites or designs. (However, the Nuclear Waste Policy Act of 1982 requires prelicensing consultation between the U.S. Nuclear Regulatory Commission and U.S. Department of Energy.)
- The U.S. Nuclear Regulatory Commission role is not to monitor all licensee activities, but to oversee and audit them. The U.S. Nuclear Regulatory Commission should evaluate whether a license application meets the applicable regulations based on a review of what is in the application. Reviews using staff audit calculations should be performed in very limited situations, such as where there are unique proposals involving new methods or assumptions. Otherwise, the U.S. Nuclear Regulatory Commission staff should review the application to ensure that assumptions are justified, methods used are acceptable and applicable over the range presented, models are properly applied, and results are acceptable. Staff can and should do quick, bounding calculations and performance assessments, and confirmatory analyses using process-level models; however, in-depth, detailed analyses can be limited to a very few applications; and
- The three outcomes available to the U.S. Nuclear Regulatory Commission at the conclusion of a licensing review are: (i) grant the license; (ii) grant the license subject to conditions agreed by the licensee; or (iii) deny the license. Other than rejecting an applicant or licensee proposal, the U.S. Nuclear Regulatory Commission has no power to compel a licensee to come forward with, or prepare, a different proposal.

The U.S. Nuclear Regulatory Commission's regulatory role in any licensing action is to apply the applicable regulations and guidance, and to review applications for proposed actions to determine if compliance with regulations has been achieved. The burden of proof is on the applicant or licensee to show that the proposed action is safe, to demonstrate that regulations are met, and to ensure continued compliance with the regulations" (USNRC, 2002; Section 1.1.1).

The current DOE target date for submittal of the license application is December 2004. The challenge is for DOE to address within this time period those key technical issues needed to submit a complete license application and to plan for filling remaining knowledge gaps. If Adaptive Staging is implemented, it is important for DOE to formalize a process to incorporate new data and information that may be learned during preparation of the license application and throughout the licensing process. This learning process relies on continuation of on-site testing and pilot activities and off-site testing with non-radioactive simulated waste.

- **Making and maintaining the safety analyses.** The USNRC requires DOE to submit two safety analyses, one for pre-closure safety and the other for post-closure safety. The principles of Adaptive Staging encourage DOE to iterate its safety analyses, and these iterations do not stop with submission of the first license application. New knowledge may, in principle, weaken or strengthen the safety analysis. Knowledge that weakens the safety case may be dealt with in Adaptive Staging by program modifications that can enhance safety. Adaptive Staging implies that DOE takes the lead in developing each aspect of the safety case, not simply providing whatever is required by the regulator. For example, although Section 4.1.2 of the USNRC's Yucca Mountain Review Plan does not specifically require a physical demonstration of retrieval and alternative storage under Adaptive Staging, doing so would be expected to yield knowledge and experience to ensure reversibility.
- **Choosing licensing stages within the current regulatory framework.** The current licensing schedule extends sufficiently far into the future to permit the incorporation of Adaptive Staging into DOE's approach. Under current schedules, the first application for construction authorization will not be submitted until December 2004, and the USNRC review and licensing process is expected to take the full time permitted by the NWPA (Section 114[d]). Hence, construction activities at the site are not expected to begin for at least five years. This period is crucial for the development of Adaptive Staging in the Yucca Mountain Project. During this period, DOE could generate new knowledge to address key uncertainties through on-site activities and the long-term science and technology program. DOE could also reflect on possible licensing mechanisms, for instance through substages or conditions of the licenses, to modify the reference design, repository operations, or the performance confirmation program.

As the USNRC points out in 10 CFR Part 63, the knowledge available at the time of construction authorization will be less than at the subsequent stages:

> "Part 63 provides for a multi-staged licensing process that affords the Commission the flexibility to make decisions in a logical time sequence that accounts for DOE collecting and analyzing additional information over the construction and operational phases of the repository. [...] The time required to complete the stages of this process [the four major licensing decisions] (e.g., 50 years for operations and 50 years for monitoring) is extensive and will allow for generation of additional information" (66 Federal Register 55738, November 2, 2001).

Nevertheless, ensuring the compatibility of Adaptive Staging with the licensing procedures already specified by the USNRC is crucial. Compatibility entails moving from the general recognition of flexibility cited above to the development of a detailed plan for the licensing process that allows Adaptive Staging. The Adaptive Staging plan in the initial application would explicitly address those changes in design, tests, and experiments that it would plan to make or conduct without obtaining an amendment of construction authorization under 10 CFR Part 63.33. Part 63.44(b)(1) sets out specific criteria for such changes, tests, and experiments.

The construction application is the first formal opportunity for the USNRC to review and adjudicate the repository at this site. The USNRC is not expected to consider reversal of this decision once made unless new information is developed that warrants reconsideration. In the regulation there are many requirements to update the analysis when applications for amendments are submitted, as well as a requirement in 10 CFR Part 63.44(c)(2) to report every 2 years on changes, tests, and experiments that were made or conducted without amendment. These updates could provide information for use at Decision Points.

The committee offers the following as an example of how the detailed plans for Adaptive Staging could be woven into the licensing stages. DOE would proceed in the next 2 years to complete its safety analysis to support the license application. In its application, DOE would provide details of a baseline design for the full repository that are sufficient to warrant issuance of the initial construction authorization. The application would include conditions that would limit construction to a section of the repository large enough to conduct cold and hot thermal mode testing. The application would request this limited construction based on confidence in the adequacy of the safety case or safety analysis for the proposed full repository, but would not yet request approval to proceed with construction of the full repository. The application would spell out the procedures DOE would follow for making changes, tests, and experiments without advance approval by the USNRC as well as those changes that DOE would seek only by application for amendment.

In parallel with the first construction application, DOE would plan for stages within the reference framework and conduct work in continuation of site characterization tests and separate off-site work. Their purpose would be to evaluate alternatives to the baseline design, such as better understanding of the site's local hydrology and monitoring needs; different thermal density limits for repository waste loading; different designs and materials for the drip shields; possible internal filler materials for the spent fuel waste packages to enhance their retention of key isotopes when corrosion finally penetrates the canister;[8] and alternatives to the designs for receipt of waste, buffer storage, handling, packaging, and emplacement that could enhance safety or reduce cost without a safety detriment. The information obtained from this work would enter into the current licensing process only if it revealed something significantly adverse to the current application. This parallel work would be transparent, inviting review and comment from all stakeholders and technical oversight groups.

Assuming that this first application for construction authorization is granted, DOE would evaluate the learning from the licensing process and the parallel work as it begins construction of the initial portion of the repository. In this example DOE would construct only that portion of the repository useful for pilot testing,

[8]For instance, depleted uranium compounds were proposed as waste package backfill by Forsberg (1995, 2000)

concentrating on developing a good safety culture for industrial safety and control of worker radiation exposures. The application would clarify the purpose of the pilot testing proposed, and DOE would conduct cold testing to confirm the adequacy of the constructed design, or identify changes that are warranted with respect to waste handling, packaging, emplacement, and recovery. Minimal cold pilot testing would be needed for facilities constructed for receipt and storage of waste, since such facilities are in widespread, licensed use in the United States.

As soon as sufficient knowledge has been obtained from pilot testing and parallel technical work, DOE would make appropriate changes to the reference design and safety analysis. It would then prepare an application to the USNRC for a license to receive and emplace waste. That license application would contain a condition that waste would be received in larger quantities but packaged and emplaced only in pilot testing. Despite this condition, the application would be justified by an adequate safety analysis for completion of construction and waste emplacement following the revised design for the full repository. Further construction of the repository beyond the pilot stage would be sought by amendment pending analysis of the hot pilot testing and parallel activities. Once this license is granted, DOE would proceed with waste receipt sufficient for hot pilot testing, but DOE might also begin receiving larger amounts of waste into buffer storage at the site if the license application included that proposal.

After conducting pilot testing, DOE would enter a stage of re-evaluation of all knowledge gained from parallel on-site and off-site work to select the design and operating techniques for constructing the remainder of the repository and for conducting full-scale operations. The appropriate license application(s) would be prepared and submitted. The staging plan laid out in the initial construction application might also include preliminary information on the subsequent application for the first license to receive and emplace waste. Because of the mechanics of the USNRC licensing process and subsequent construction and test activities, this application is not likely to be filed until four or five years after the initial application, perhaps by 2009. The experience gained in previous stages may be incorporated into the experience gained during construction.

Some potential difficulties with implementing Adaptive Staging are related to the procedures of the USNRC licensing hearings. For the licensing actions—construction authorization and license to possess and emplace waste, and amendments—the USNRC is expected to use a formal hearing process before an Atomic Safety and Licensing Board to litigate and adjudicate the soundness of the license application. The litigation process has the effect of freezing, during the USNRC licensing review, the repository design and its safety analysis, as well as the filing of contentions by any parties that have been granted standing to intervene. This design freeze can inhibit Adaptive Staging by delaying design adaptations while the hearing process proceeds. If new information adverse to safety becomes available during licensing process, DOE would have to introduce new information and basis for revision into the proceedings. Therefore, before implementing Adaptive Staging, it is important that DOE and the USNRC consider the consequences of Adaptive Staging on the licensing hearing process.

In summary, by implementing Adaptive Staging, DOE could possibly achieve earlier resolution of key licensing issues. Early planning is necessary for Adaptive Staging to be as effective as possible in addressing the licensing challenges.

5.4.3 Planning for interim or buffer storage requirements

Challenges facing DOE with respect to surface storage of high-level waste and spent fuel are:

- planning for sufficient buffer storage to provide the required flexibility for repository operations;
- working with utilities, regulators, and legislators to establish feasible acceptance schedules; and
- choosing and implementing appropriate storage technologies.

Once the license to receive and possess waste is obtained, the rate of emplacement and the thermal operating mode can be varied more flexibly if there is sufficient on-site buffer storage (i.e., storage of waste received from off-site pending receipt inspection, repackaging, and preparing for emplacement).

Adaptive Staging may require a larger buffer storage capacity at or near the site, unlike a Linear Staging approach that is based on "just in time" waste deliveries. There appears to be a rationale for DOE to propose Adaptive Staging with a large buffer storage at or near Yucca Mountain. The NWPA (Section 114[d]) directed that the capacity of Yucca Mountain, if licensed, should be limited by the USNRC to no more than 70,000 MTHM until a second repository is in operation. That restriction defines the 70,000-MTHM limit to include any monitored retrievable storage facility within 50 miles of the repository.[9] Therefore, the 70,000 MTHM limit for Yucca Mountain includes not only all waste emplaced in the repository, but also all waste received for buffer storage at or near the site while awaiting packaging and emplacement. Under the terms of the first license to receive high-level waste, buffer storage of waste as shipped, or in wet or dry storage at the surface, could be legally acceptable at Yucca Mountain so long as it remains within the 70,000-MTHM limit.

One of the challenges for DOE is to begin waste shipment as soon as practical and at rates adequate to remove pressure from the utility sites. The first shipments could be sent to the buffer storage at the site as soon as the repository receives the first license to receive and emplace waste. The shipment rates could be higher than those currently planned, even if the authorized quantity of waste for packaging and emplacement is limited by a potential licensing condition.

One of the challenges in managing buffer storage requirements is the policy implication of receiving a license for a slow rate of emplacement but engaging in a high rate of acceptance into buffer storage. If DOE decides to receive a very large fraction of the 70,000 MTHM into buffer storage once the license is received, while only emplacing a few hundred MTHM, it could appear to be establishing monitored, retrievable storage at the surface. While Adaptive Staging cannot guarantee that this perception will be avoided, DOE can transparently justify *in situ* buffer storage because of the slower emplacement rates introduced by Adaptive Staging while repository construction continues. Adaptive Staging would offer stakeholders and technical oversight groups the opportunity to be involved in the development of the buffer storage program, for instance, by providing input on the volume of waste on the surface, the receipt rate, and underground emplacement rate. The added

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[9]This restriction from Section 114(d) of the NWPA is different from the restriction derived from Section 141 of the NWPA, which forbids the siting of a separately licensed, monitored retrievable storage facility in a state holding a candidate repository.

transparency could help forestall the perception that DOE is setting up monitored retrievable storage at the surface.

A further issue relevant to the buffer storage at Yucca Mountain is that of recent concerns over terrorist activities. Security concerns might result in pressure to move the waste underground as quickly as possible, rather than at a rate determined by the need to gain experience in repository operations. The counter-arguments to these points are that security would, in any case, be as good as, or better than, at many distributed surface stores and that additional special "hardening" measures could be taken at Yucca Mountain, if necessary.

5.4.4 Constructing the repository and beginning operations consistent with current schedule and the budget

In common with many other repository programs, the U.S. program has experienced an escalation in cost estimates and schedule slippage. The challenges to DOE following this experience are:

- producing and keeping to a credible program schedule allowing for changes and for stakeholder interactions, which are an integral part of repository implementation;
- setting transparent, well-justified goals, principles, and practices to help stakeholders understand reasons for possible deviations;
- documenting and justifying the budgets for each activity and for the overall program to assure auditability; and
- completing any activity undertaken on or ahead of schedule to avoid cost increases.

If Adaptive Staging is employed, an effective and efficient repository development program integrates all elements of the waste management program into a cohesive unit. Careful, iterative system analysis of options must be used to balance competing considerations such as costs, schedules, emplacement rates, and other institutional and societal considerations.

Current cost estimates total approximately $60 billion (in year 2000 dollars) for the Yucca Mountain project until the site is released from all controls. Cost estimates have already increased by 26 percent since 1998 (DOE-OCRWM, 2001a). The schedule has slipped from 1998 to 2010 for the first waste shipment to Yucca Mountain. A major challenge for DOE is to maintain the current schedule. DOE estimates that every year of delay will cost $35 million (DOE-OCRWM, 2002b). A further problem for DOE is that the budget is approved each year by Congress and may fluctuate unpredictably, depending on several factors (e.g., politics, economics, year's events) that are outside of DOE's control. The schedule can also be affected by lawsuits from the states, the public, and utility companies. These lawsuits can be lengthy and distract DOE from its programmatic activities.

Adaptive Staging could help address these challenges through an incremental buildup to full-scale operations. Costs would increase more slowly than if the underground and surface facilities were built progressively as waste is received and experience is gathered. An incremental buildup may lead to higher integrated early costs, but it could actually accelerate the schedule and reduce costs in the long-term because the slow buildup may allow problems to be identified and corrected before they become expensive or time consuming. This cost-reduction potential is present because Adaptive Staging attributes and Decision Points (Sections 2.2 and 2.3) are designed to make large-scale, costly mistakes less likely than if Linear Staging were used. A pilot stage could be used to correct for reduced-scale mistakes and to learn from them. The attribute of systematic learning with its final goals of improving the safety of the repository and optimizing operations may also lead to a more cost-effective repository. The learning process would explicitly include safety as well as cost optimization.

Linear Staging could be the cheapest and fastest way to achieve a goal when everything goes as planned. It is more realistic to assume that unexpected results will occur, and there are many examples in DOE's history and elsewhere to demonstrate this likelihood.

5.4.5 Designing and implementing the transportation plan

The prime challenges facing DOE in transportation are:

- choosing modes of transport and transport routes;
- interacting with the numerous states and affected communities;
- demonstrating convincingly the safety of transport; and
- implementing a complete, reliable national waste transportation system.

With congressional approval of Yucca Mountain as the repository site, transportation of spent fuel and high-level waste to the repository has become one of the more contentious issues facing the program. A multitude of stakeholders and states will be affected and concerned as a final transportation plan is formulated and adopted. While many of the aspects of transportation are governed by existing regulations and commitments, many important issues remain to be resolved. Among these are the mix of transport modes (i.e., train, truck, or both), routing, and interactions with state agencies on such issues as notification, security and emergency response training, and frequency of shipments through affected jurisdictions. The transport strategy may also be affected by waste-specific issues, such as the type and characteristics of waste to be delivered to the site (e.g., to optimize the thermal loading) and by the location of facilities for conditioning and packaging the waste.

DOE could use Adaptive Staging to help address these transportation challenges. For example, once buffer storage capacity is available at the site, a pilot transportation plan could be implemented to test its viability. As one option, transporting small amounts of waste (e.g., for the pilot stage) would allow the logistics and routing of truck or rail transport to be evaluated before committing to a final approach. Initial shipping and buffer storage at or near the site can be conducted using techniques and equipment that are already certified by the USNRC (10 CFR Parts 71 and 72). The currently designed truck casks carry only 1 to 2 MTHM of spent fuel; currently certified rail casks carry 10 to 20 MTHM of spent fuel. Another option is for DOE to make an early start on a higher rate transportation program by going directly to rail shipment.

Adaptive Staging principles offer a framework for the numerous and contentious negotiations with the affected communities in developing the transportation plan (Section 4.4). The pilot stage offers an opportunity to engage parties affected by shipments of waste and to gather their input about preferred transportation alternatives within the bounds of regulation and acceptable cost. For example, exercises with state emergency response teams could identify issues needing attention before full-scale shipment commences. Additionally, stakeholder participation in the transportation plan may also help uncover and address unrecognized issues before obtaining the license to ship waste. In the end, such negotiation could result in more acceptable routing, thus enhancing public acceptance and improving credibility for DOE.

5.4.6 Working to maintain and demonstrate scientific and institutional credibility

The safety of any geologic repository is evaluated on the basis of numerous complex scientific studies. One of the conditions, necessary but not sufficient, for enhancing public acceptance of the repository is to have a credible, thorough, and well-communicated scientific program. Based on the information gathered by the committee, there appears to be a perception that some parts of the Yucca Mountain scientific program could be improved. For example, the NWTRB stated, "when the DOE's technical and scientific work is taken as a whole, the Board's view is that the technical basis for the DOE's repository performance estimates is weak to moderate at this time" (NWTRB, 2002). An international peer-review group was of the opinion that in DOE "relatively little emphasis is placed on the important issue of presenting an understanding of system behaviour" (NEA, 2002). The Advisory Committee on Nuclear Waste[10] (ACNW) also stated that "the supporting evidence for many assumptions [in DOE's performance assessment] is often obscure. Our position is that the contribution to risk from coupled processes should be quantified and made transparent" (ACNW, 2002).

DOE's scientific program has been criticized primarily with respect to:

- the completeness of the scientific investigations;
- whether there is sufficient investigation of data that do not match current theory;
- whether alternative interpretations of the data could lead to other also credible theories and explanations that might show less confidence in performance;
- the level of confidence attached to the conduct of total system performance assessment (TSPA); and
- limits in the effectiveness of the program to describe and communicate its scientific and analytical evidence and rationale in an understandable, accessible, and compelling fashion.

Adaptive Staging highlights attributes of a repository program that could improve perception of DOE's scientific credibility:

[10]The ACNW is the independent technical advisory group for the USNRC. Its members are appointed by the USNRC commissioners.

- Transparency, or openness, of documentation for decision-making and availability of research data and results in technical and non-technical media for review by peers and the public. This transparency would clarify and document the scientific rationale underlying decisions on technical issues.
- Auditability, or publication of scientific results in peer-reviewed literature and increased reliance on external scientific panels to review scientific progress and data interpretation. Science supporting the performance assessment and the performance assessment methodology itself would be peer reviewed before it is used in a license application.
- Stakeholder involvement, or making scientific data available to stakeholders (see Sidebar 5.2) and outsiders. Involving interested parties promotes openness and could lead to wider acceptance of the program.[11]
- Integrity, e.g., funding and support to create an independent technical oversight group. This oversight group could help assure that scientific objectivity and neutrality are maintained.
- Responsiveness, or systematic and continued learning through a science program that provides feedback to the decision-making process in a timely manner. Responsiveness also implies that the science program is open to new questions and paths of inquiry, based on peer review.
- Flexibility, or incorporating new knowledge and scientific understanding to enhance safety as a management priority. Alternatives are always open for examination and options can nevertheless be chosen even in the face of uncertainties, provided management maintains reversibility as an option.
- Commitment to systematic learning, or encouraging and supporting scientific curiosity. Scientific curiosity drives the learning process and permits new hypotheses to be developed and tested. Learning would be focused on reducing uncertainty in key areas and on distinguishing unexpected and new findings that require management response and adaptation from findings that would not impact the current program strategy. Adaptive Staging also implies openness and involvement with international communities.

An independent long-term science and technology program, which DOE is currently putting into place in parallel with its science program to support the license application, is consistent with Adaptive Staging.[12] This long-term science and technology program may enhance DOE's scientific credibility, yet its goals may be farther-reaching and more specific. The long-term science program could be the basis for providing data, or the program could be focused on fundamental research on key issues aimed to reduce uncertainties that affect safety. Finally, such a program would not be diverted by short-term problems.

Technical research could be directed to such goals as materials development, testing of engineered barriers, and verification of performance assessment. If the science program is allowed to challenge operational procedures, and to subject its findings to peer review, the potential exists for confidence in DOE to increase and for additional scientific credibility to accrue. In addition, Adaptive Staging is

[11]Plain English documents including a safety case for a broad audience could make an important difference in stakeholder confidence.

[12]DOE's Office of Civilian Radioactive Waste Management is currently setting up a long-term science and technology program (Nuclear Waste News, 2002). The committee supports this initiative.

consistent with quality assurance guidelines, ISO standards, and peer-review methods that improve the traceability, transparency, and confidence in scientific results.

Scientific credibility can also be increased by establishing a technical oversight group and a stakeholder advisory board. The State of Nevada, for example, could provide important input on the structure, scope, and reporting relationships of this group. DOE could benefit in societal and programmatic ways by formally incorporating local affected stakeholders into a long-term data acquisition and monitoring program.[13]

The long-term science and technology program would also include a social science component addressing methods to monitor and include stakeholder and public input for key decisions when moving from one stage to another.

It must also be acknowledged that improving DOE's openness is a challenging task that will require investment of additional effort with or without the implementation of Adaptive Staging. For example:

- Designing a transparent and auditable long-term science program requires skills and experience of DOE program management that may differ from those most emphasized in the past.
- Publishing in scientific journals and other peer-reviewed activities take time and effort.
- Publishing in scientific journals as a criterion for evaluation of success at program milestones requires management involvement and encouragement.
- Documenting the scientific basis for decisions is time consuming.
- Providing public access to data might raise questions and claims lacking scientific bases that must be resolved; this process, too, may be time consuming and may also conflict with confidentiality issues.
- Researching, monitoring, and responding to stakeholder and public perceptions can also be time consuming.

Credibility-building actions take time and cost money, which must be factored in the reference framework planning. But in the long term they could enhance safety and public confidence in the repository.

5.4.7 Working to maintain effective working relationships with the nuclear power utility companies

The challenges facing DOE in its interactions with the utilities, the principal generators of most of the waste for disposal, include:

- providing an acceptably safe repository for commercial spent fuel,
- keeping costs to justifiable levels,
- accepting spent fuel as soon as possible, and
- avoiding the need for construction of unnecessary intermediate storage facilities at nuclear plants or in central locations.

[13]DOE is already collaborating with Nye County, Nevada, on these issues.

Can the adoption of Adaptive Staging help DOE meet these challenges? When this committee began work on this study, the DOE baseline strategy employed Linear Staging on an ambitious schedule, seeking construction authorization for the entire repository, a license to receive and emplace waste as soon as a sufficient part of the repository was constructed, and receipt of the waste afterward at the maximum practical rate. A prime objective of this strategy was to enable DOE to accept spent fuel from the utilities as soon as is practical.

DOE is currently in litigation with the utilities for failing to begin removal of commercial spent nuclear fuel from the reactor sites by 1998, the deadline set by the contracts entered into under the Nuclear Waste Policy Act. DOE is striving to maintain a schedule that will lead to the first receipt of waste at Yucca Mountain by 2010. Therefore, DOE has limited time[14] to apply for and obtain a license to receive and emplace waste. One of DOE's top priorities is to begin shipment of spent fuel to Yucca Mountain by 2010, rather than have a full system, including all surface facilities, implemented at that date.

Development of a licensed pilot facility and sufficient on-site buffer storage could help DOE meet the 2010 deadline for shipping waste from generator sites. By decoupling waste shipments from underground emplacement, shipments could begin sooner. Adaptive Staging would not delay the receipt of a license to receive and emplace waste, but it would likely lower the initial rate at which waste could be packaged and emplaced in the repository. Attempting to develop and freeze a final packaging and emplacement design could delay construction of the full-scale surface and subsurface facilities for packaging and emplacement.

The development of the buffer facility could itself be managed with an Adaptively Staged approach, nested in the bigger Adaptive Staging of the entire repository system, thereby increasing opportunities for involvement with stakeholders and utility companies, which may result in increased confidence and better and more cost-effective repository operations.

5.4.8 Improving working relationships with stakeholders and the general public

The challenges that DOE faces in this area are:

- enhancing the credibility of DOE as an institution,
- establishing and maintaining nationwide credibility for the high-level waste disposal program, and
- interacting directly with stakeholders in the local communities and in the State of Nevada.

DOE has long experienced a hostile attitude from some stakeholders in Nevada and from parts of the general public because of the Yucca Mountain Project. Stakeholders and members of the public from the State of Nevada have so far

[14]According to the information gathered the license application will be submitted in December 2004 (Williams, 2002). From this date, the USNRC has until March 2005 to verify the completeness of the application plus 3 (and up to 4) years to process the construction application and authorization; which means that the entire process could end in 2008 or 2009, at least 5 years from the present (2003).

engaged in limited effective discussions with DOE on the design and operations of the repository. There are two problems associated with public involvement in the Yucca Mountain project: (1) there is no state organization collaborating with DOE on the Yucca Mountain Project and (2) the state has shown reluctance to cooperate on planning and oversight activities for the Yucca Mountain Project. One possible reason for the lack of constructive cooperation between DOE and the State of Nevada is that the final decision to concentrate the U.S. effort at Yucca Mountain is perceived by some as a purely political decision, with little direct input from the public (although strongly supported by its representatives, except for Nevada's, in Congress) and with too little independent technical input.[15] Although all states proposed as initial candidate sites were opposed to the repository siting effort (see Appendix F, Section F.1.2), it has been argued that Nevada's intransigence with the federal government is due particularly to broken agreements and trust-decreasing actions since the beginning of the U.S. nuclear program (Makhijani and Saleska, 1999). However, even though the State of Nevada has refused to engage with DOE, the communities in Nye County, where Yucca Mountain is situated, are collaborating productively with DOE (Nye County, 2002).

Establishment of a stakeholder advisory board could also enhance participation and provide opportunities for DOE to demonstrate that it has completed specific actions in the agreed manner. One of the main functions within the scopes of the stakeholder advisory board is allowing effective communication between DOE and stakeholders. In presentations to the committee, some stakeholders said that DOE had not yet offered them true participation, only one-way communication. Through such an advisory board, stakeholders would be given the opportunity to comment on operational details such as the transportation routes, emergency response preparedness, protection of workers and the public, and other repository operations. The establishment of an independent technical oversight group could also be a great benefit in this matter.

With increased opportunities to influence the repository program, residents of Nevada and of the most affected counties may be more willing to participate on an advisory board. The committee recognizes that DOE has expressed its willingness to support local oversight and advisory groups and that implementation requires a breakthrough in its dispute with the State of Nevada.

[15] See, for instance, the report *High-Level Dollars, Low-Level Sense* (Makhijani and Saleska, 1992).

6

Findings and Recommendations

In this chapter the committee summarizes its findings and provides recommendations for the staged development of a generic repository program and specifically for the Yucca Mountain Project. The purpose of this study is to discuss staged approaches to implement a successful repository program. Therefore, findings and recommendations are preceded by the committee's definition of a successful repository program.

6.1 Committee's definition of a successful geologic repository program

First and foremost, the absolute measure of success of a geologic repository is the extent to which it isolates the waste from the accessible environment as far into the future as the waste remains hazardous. A more useful definition of success for the implementer is a safe geologic repository that is also cost-effective and is societally acceptable. More concretely and more measurably, a successful geologic repository program is one in which:

- a geologic site and engineered system, judged to be technically suitable using the particular country's accepted regulatory, public, and political processes, have been identified;
- operational and long-term safety aspects are consistent with current scientific understanding of repository systems, safety features are reviewed, and the necessary licenses are granted;
- an ongoing long-term monitoring and observation program designed to substantiate the current scientific understanding of the safety aspects of the repository system is in progress;
- sufficient societal consensus is achieved to allow operations to begin and continue;
- initial waste emplacement has taken place with plans for reversibility; all necessary safety and security measures are set up to emplace additional waste, if decided; and
- procedures and funding arrangements are agreed to for either:
  -backfilling (if used), closing, and sealing the repository[1] (if technical and societal confidence in its long-term isolation properties continues); or

[1]Procedures for closing and sealing the repository include additional measures such as providing longer-term accessibility of records relevant to the site.

-maintaining long-term control and monitoring and capability for retrieving wastes, if this capability is necessary for technical or societal reasons.

The committee's definition of a successful repository *program* is different from the definition of a successful *repository* itself. Success of the repository will be known only far into the future, after thousands of years have passed without significant release of radionuclides into the accessible environment. The committee's definition of a successful *program* emphasizes the goal of achieving the required degree of technical and societal consensus to begin waste emplacement and the incremental improvement of waste emplacement operations, rather than moving rapidly to full-scale emplacement. Repository implementers often view the latter as a measure of success.

6.2 Adaptive Staging offers a promising approach to successful geologic repository development

1. Compared with other large engineering projects, geologic repositories for high-level waste are peculiar undertakings because (1) they are first-of-a-kind, complex, and long-term projects that must actively manage hazardous materials for many decades during the operational phase; (2) natural and engineered barriers are expected to hold passively safe these hazardous materials for many millennia after repository closure; and (3) they are widely perceived to pose serious risks. As with other complex projects, repository programs should proceed in stages.
2. There are two possible approaches to Staging: Linear and Adaptive. The Adaptive Staging approach laid out in this report is characterized both by specific attributes (see Section 2.3) and by a formal decision-making process between stages (see Section 2.4). These attributes are: commitment to systematic learning, flexibility, reversibility, auditability, transparency, integrity, and responsiveness. Taken separately, these attributes do not constitute the process that the committee calls Adaptive Staging. Only the presence of all these attributes makes the staging process Adaptive. Stages are separated by Decision Points. Decision Points need not be fixed in time: they can be introduced when new information warrants them. Decision Points provide an opportunity to integrate newly acquired knowledge into the program and to evaluate the program's status. Adaptive Staging anticipates and facilitates integration of such new knowledge and periodic program evaluations. Decision Points are intended to focus the implementer's attention on the goal of identifying program improvements with respect to, for instance, environmental impacts, safety, costs, or schedule.
3. Adaptive Staging is a cautious, deliberate decision and management process that emphasizes continuous learning, both technical and societal, includes scientific and managerial re-evaluations and responses to new knowledge, and is also reversible by design.
4. Certain criteria can suggest when Adaptive Staging is more promising than Linear Staging for managing complex projects (see Section 2.5). The technical and societal contexts of geologic repository development in most coun-

tries meet the criteria set out in Chapter 2 for using Adaptive Staging. Adaptive Staging can be applied to all parts of a repository system, affecting scientific, technical, societal, and institutional aspects of the process. Adaptive Staging is not in itself sufficient to guarantee the success of a repository program, but the committee believes it increases the likelihood of success.

5. Previous approaches to repository development, often based on a Linear Staging approach, have encountered serious obstacles. Increased use of staging is apparent worldwide, as described in Appendix D.

6. While the committee believes Adaptive Staging is a promising approach, it also recognizes that Adaptive Staging is a new and unproven process. Nevertheless, the Adaptive Staging strategy is consistent with any project management approach that requires simultaneous attention to societal, institutional, and technical concerns. The Adaptive Staging approach in repository development also has features in common with environmental management concepts proposed in the recent ISO 14000 standards, which also emphasize commitment to systematic learning and to looking beyond simple compliance with regulations. Finally, when the project under consideration meets the criteria for Adaptive Staging (Section 2.5), then the use of Adaptive Staging is consistent with good engineering practices.

6.3 Effective Adaptive Staging involves the entire waste management system

1. Adaptive Staging has an impact not only on repository operations but also on transportation and buffer storage at both reactor and repository sites. Full and transparent consideration must be given for understanding the implications of the staging process on all of these system components.

2. To be effective, Adaptive Staging must involve the implementer, the regulator, stakeholders, and the concerned general public. The success of Adaptive Staging depends on the extent to which involved parties are willing to acknowledge remaining uncertainties and recognize unexpected outcomes and occurrences as learning opportunities to improve the system.

3. Adaptive Staging has a clear impact on the program's initial schedule because it encourages a slow buildup of activity. However, the longer-term impacts are less clear. Adaptive Staging is a means to bring the new information into the program in a timely fashion, which could result in more timely and informed decision-making, thereby increasing program efficiency. The committee is not in a position to analyze specific cost implications but recognizes the need for cost and decision analysis studies in this domain. The judgment of the committee is that Adaptive Staging need not increase costs; it may do so in the short term, but it may also serve to avoid expensive errors over the long-term or reduce delays (and hence costs) caused by programmatic inefficiencies or societal conflicts. Cost estimates for repository projects often prove unrealistically low because they are based on assumptions that the project will proceed as planned in advance with no deviations, an assumption that is seldom achieved. The use of Adaptive Staging may reduce the time and costs to initial waste emplacement.

4. Adaptive Staging may play a more pronounced role in the early stages of the operational phase. As a program progresses through the early stages of the multi-decade operational phase, it is anticipated that early successful stages are likely to lead to subsequently longer stages. Alternatively, unanticipated, significant discoveries or problems would be expected to lead to both careful evaluation of future activities and shorter stage durations.
5. Adaptive Staging will probably not have any major negative impacts on security. It has been argued that the security of nuclear materials is easier to ensure if they are emplaced deep underground; thus, those materials should be emplaced in a geologic repository as soon as they are ready for disposal. Therefore, it is necessary to consider whether adopting Adaptive Staging could greatly affect the time frames during which different types of wastes (defense high-level waste or spent fuel versus commercial spent fuel) are emplaced underground. Independently of the management approach chosen, the time that will elapse before geologic repositories will begin to operate is so long (i.e., decades) that other, more immediate, measures are needed to prevent misuse of radioactive materials by terrorists. Therefore, any plausible delays in moving wastes underground because of Adaptive Staging will not significantly impact the safe and secure geologic disposal of nuclear materials.

6.4 Iteration of the safety case is central to Adaptive Staging for geologic repositories

1. The committee addresses safety using the term "safety case," in accordance with growing international practices, to mean the integrated collection of all arguments that the implementer produces to demonstrate safety of the repository to all interested parties. Iterative assessment of the safety case is the fulcrum around which decisions are made. This means that the safety case is used in Adaptive Staging as a management tool to guide the implementer's actions during repository development. The safety case is also used to develop a program with features such as robustness and conservatism and to convince the implementer itself, the regulator, stakeholders, and the general public that there is a sensible and defensible set of arguments showing that the repository will be safe. The safety case includes a broad and understandable (to stakeholders and the general public) explanation of how safety is achieved and a similar discussion of the uncertainties that result from limitations in the scientific understanding of system behavior.
2. Iterative review of the safety case is a key aspect of Adaptive Staging. During a Decision Point, the implementer conducts a systematic re-evaluation of the safety case in view of new information gained during the previous stage and adapts the program, if necessary. This re-evaluation in turn guides data collection in the next stage. Periodic reassessment of the safety case allows fruitful incorporation of new knowledge and guides changes to the program. By reassessing the safety case at each stage of repository development the implementer can evaluate the robustness and reliability of the system concept in light of new data, identify any unresolved technical safety issues, and address issues of concern raised by the regulator, stakeholders,

or the general public. The safety case is used to convince the implementer itself, the regulator, stakeholders, and the general public that there is a sensible and defensible set of arguments demonstrating that the repository will be safe.

3. A critical aspect of safety case review is that the program not only specifies new data to collect but also allows for hypothesis falsification and testing concerning repository performance. The comparison of observation and prediction may occasionally bring unexpected discoveries that yield useful information on predictions of repository behavior. Over time, as stages are completed, the ability of the program to predict performance should improve. This improvement in turn increases confidence in the robustness of the safety case.
4. Re-evaluation of the safety case implies neither repeated questioning of earlier decisions nor necessarily a pause in program activities, and in no case should this re-evaluation be used to unnecessarily delay decisions. The purpose of the re-evaluation is to examine the current situation and to ensure that any significant changes in original program goals or philosophy are based on new knowledge and understanding of the system and do not result inadvertently from cumulative incremental changes.

6.5 Adaptive Staging requires continuous and active learning in both technical and societal fields

1. The commitment to systematic learning is reflected in an ongoing program monitoring the engineered and natural barriers of the repository system. A concurrent long-term science and technology program is also established to analyze and interpret system behavior; recommend system improvements in response to new information; and address knowledge gaps.
2. Important new scientific and technical information for Adaptive Staging will emerge from technical monitoring of the system, some will arise from specific studies before and during the operational phase, and some will result from experience gained throughout all stages.
3. The long-term science and technology program should include parallel research and monitoring functions in the social sciences and other relevant research fields to enhance the societal and institutional consideration of program development.

6.6 Adaptive Staging encourages opportunities for interactions with stakeholders and the general public

1. Stakeholder input to the decision-making process is of paramount importance for effective implementation of Adaptive Staging. An essential component of systematic learning is proactively seeking stakeholder involvement, rather than limiting involvement to public information meetings such as hearings or comment periods, which are often characteristic of Linear Staging.

2. Adaptive Staging encourages and explicitly calls for interaction with stakeholders and the general public at Decision Points (see Figures 2.1a, b, and c). Such involvement holds the potential for advancing social science knowledge and for enhancing public trust. Complete trust is not a prerequisite for Adaptive Staging; however, some trust is required to initiate this approach because the flexibility attribute of Adaptive Staging implies that end points and paths are not rigorously defined at the outset of the program. If stakeholders recognize their right to provide input to program decisions, they may be more likely to acknowledge the benefits of Adaptive Staging, may develop greater trust in the implementer and the process, and may acquire more confidence in the safety of the repository.
3. Adaptive Staging, with its focus on learning, provides increased opportunities for building institutional continuity—an essential requisite for long-term projects in which trust must be built and maintained and information passed on over multiple generations.
4. Adaptive Staging increases the knowledge base in the project through stakeholder involvement. This includes not only technical knowledge augmented by open contacts with the scientific community but also societal knowledge gained from interacting with key stakeholders and the general public.
5. Adaptive Staging can have adverse impacts on program development because it affords increased opportunities for program opponents to delay or hinder progress. Stakeholders and the general public may question the implementer's motivations for adopting Adaptive Staging. They may view the use of Adaptive Staging as a way to get "a foot in the door," that is, to begin waste emplacement before important uncertainties have been resolved and as a way to take larger, irrevocable steps to completing waste emplacement. To reduce the likelihood of such assertions, the grounds for Adaptive Staging must be transparently presented, the importance of reversibility (returning to a previous stage) must be stressed with the greatest attention to fairness, and the integrity of the implementer must be high.
6. Stakeholder participation is monitored and evaluated in a formal assessment process (involving stakeholders). Procedures for interactions would be improved based on what is learned from previous stakeholder and public interactions.

6.7 Adaptive Staging can be compatible with current regulatory systems

1. All regulators for geologic repositories face the "regulator's dilemma," that is, how to organize a regulatory approach that will enable sound and acceptable regulatory decisions to be made in light of uncertainties, some of which are in fact not resolvable (NRC, 2001). As a result, all regulatory systems for geologic repositories are staged from site selection, through repository development, to closure. Adaptive Staging can be compatible with current regulatory systems if regulators are responsive to the development of new knowledge and reduction of uncertainties at succeeding steps of the repository program. For Adaptive Staging to be effective, the regulatory system

must allow licensing processes that are not overly complex or long. The licensing process must accommodate the possibility of continuing the repository program during the license amendment process, provided no negative safety impacts result and no irrevocable new developments occur.

2. The staged approach to licensing allows the implementer to develop, and the regulator to review, the knowledge base and the safety case at each stage in the lengthy phases ultimately leading to closed and sealed repositories. Adaptive Staging provides a transparent, traceable record of decisions and their rationales. It also provides a continuous opportunity for stakeholder interaction with the regulator.

The previous findings are generic, applicable to any repository program, including the Yucca Mountain project. The following are *additional* findings and conclusions specific to Yucca Mountain repository program (see details in Chapter 5).

6.8 DOE has recognized potential advantages of staging

1. DOE has recognized advantages of staging its Yucca Mountain Project and has taken some actions consistent with Adaptive Staging. The original DOE justification for the flexible repository design (see Appendix F) was based primarily on cost considerations. Many aspects of the Yucca Mountain Project, however, still reflect a Linear rather than an Adaptive approach to staging. This is, in part, due to the political and legal constraints imposed on the project (see Sections 5.3 and 5.4).
2. DOE is facing many challenges with transportation, interim storage, and interaction with the utilities and the public as it moves into the license application phase for Yucca Mountain. Some of these challenges could be addressed by incorporating Adaptive Staging into the program (see Section 5.4).
3. DOE could introduce Adaptive Staging now. It will take a minimum of two years before a license application for Yucca Mountain is filed. Several years of licensing interaction with the Nuclear Regulatory Commission (USNRC) will then occur. If DOE receives a license for Yucca Mountain, there will be a multiyear buildup to full-scale operations. Operations will last for decades, and DOE has suggested a pre-closure observational period of up to 300 years. Thus, there is time for DOE to adopt Adaptive Staging in the first license application, and there is a long time span over which DOE can continue to follow Adaptive Staging and to specify in detail what the future stages and transitions will be—recognizing that with staging, future learning and adaptation may change the details of the initial plans.
4. The U.S. licensing process already follows a staged approach. Adaptive Staging presumes that a license will be issued based on safety analyses covering the entire proposed inventory (i.e., the application for the construction authorization must present complete safety analyses for pre-closure and post-closure compliance to the USNRC). The regulator, the Nuclear Regulatory Commission, expects the license application to be "as complete as possible in light of information that is reasonably available at the time of docketing" (66 Federal Register, p. 55739). This implies an expectation that

additional relevant information will become available and be used as the project develops. There is no provision for partial licenses, but the USNRC can impose license conditions requiring subsequent reviews of results obtained in earlier stages before proceeding to the following ones. Even without the imposition of such conditions, there are no restrictions precluding DOE from implementing Adaptive Staging, and DOE has the flexibility to do so voluntarily.

6.9 Specific impacts of Adaptive Staging on the U.S. program

Specific changes would result from implementing Adaptive Staging in the U.S. repository program. If adopted, Adaptive Staging would lead DOE to do the following:

- Highlight the goal of ensuring safety and security at all times more prominently than the specific milestone of emplacing 70,000 MTHM in Yucca Mountain.
- Focus more strongly on achieving the degree of technical and societal consensus needed to begin waste emplacement, rather than on the emplacement of all waste.
- Introduce stages that explicitly focus on what can be learned about safety (i.e., re-evaluating the safety case) and about concerns by the regulator, stakeholders, and the general public.
- Start conservatively in design and operations, with the opportunity to reduce conservatism as new knowledge allows.
- Plan for early pilot and test facilities along with possible demonstration facilities; clarify with the USNRC how the use of these facilities could affect the licensing process.
- Focus specifically on assuring and demonstrating retrievability.
- Focus on explicit thermal load management alternatives.
- Plan for sufficient buffer storage at or near the site, with transparency about its policy implications, and decouple the rate of waste acceptance from the rate of waste emplacement underground.
- Place high priority on defining and securing funding for the monitoring and the science (including social science) programs with the intention of modifying and improving the programs as learning progresses.

6.10 Recommendations: general

The following are general recommendations concerning the implementation of Adaptive Staging in a generic repository program.

1. **Adaptive Staging should be the approach used in geologic repository development.** The committee believes that the features of Adaptive Staging have the potential to address the technical and societal challenges of geologic repository development. This belief is based on the committee's knowledge of repository programs worldwide, considerations of other com-

plex projects, and the compatibility of Adaptive Staging with the principles of sound project management and good engineering practices. In a first-of-a-kind, controversial, and unique scientific and engineering undertaking, there are obvious benefits in starting slowly; undertaking pilot activities; designing in flexibility and retrievability; looking for alternative paths; learning from experience, science, and monitoring; and seeking and responding to stakeholder concerns.

However, Adaptive Staging has not yet been implemented in a geologic repository development program. Adaptive approaches have been applied with mixed and incomplete results in environmental and conservation management. Implementation of Adaptive Staging will likely entail new and significant organizational and institutional challenges. For instance, learning will be minimal unless the implementer actively seeks out alternative viewpoints, openly acknowledges errors and uncertainties, specifically addresses societal issues, and organizes and undertakes relevant research to improve the knowledge base.

Moreover, the long time scale of repository operation implies that organizational performance will need to be maintained over decades, and possibly centuries. Stability on this order is not the norm in corporations or governments. Hence, lessons of successful organizations and transferability of these lessons are useful areas of study. Adaptive Staging is clearly helpful with technical matters, but it can also help the program accommodate changing political factors.

While there are opportunities for implementing Adaptive Staging throughout the program, these are especially numerous in the early stages leading to full-scale operations. Adaptive Staging will also be of increased importance as repository closure decisions are made. Lacking empirical testing for Adaptive Staging, the committee recognizes that its recommendations must be accompanied by the above caveats. Moreover, the committee identified knowledge gaps in the implementation of Adaptive Staging (Section 4.1). However, the inherently self-correcting nature of Adaptive Staging reduces the risk of using this approach.

2. **A repository program should be based on a structured decision-making process that places emphasis on iterative review of safety for the entire repository system.** One essential feature of Adaptive Staging is the periodic re-evaluation of safety to guide the program at Decision Points. The committee believes that the safety case, as described in this report, is an appropriate tool for implementing this re-evaluation. The committee recommends that program implementers present a safety case for a full-inventory repository in parallel with the license application. A full-inventory safety case is important to help establish confidence by the regulator, stakeholders, and the general public in the ultimate safety of the entire repository system.

3. **The repository program should make full use of learning opportunities offered by *in situ* testing.** Adaptive Staging takes advantage of the learning opportunities during the buildup to full-scale implementation to improve

operations, enhance safety, or both. Examples of learning opportunities for *in situ* activities include (see also Section 4.2.1):

- a pilot facility for learning how operations can be most efficiently and safely performed and for identifying methods to incorporate societal learning into the process; pilot activities can begin with non-radioactive experiments but must ultimately use radioactive materials;[2]
- a test facility for short- and long-term scientific research aimed at reducing residual uncertainties and improving performance in key areas; and
- a demonstration facility for enhancing the confidence of both stakeholders and the general public in the safety of the actual repository operation and allowing particularly comprehensive monitoring of specific system components during the multi-decade operating life of the repository.

Considerations should be given for locating these *in situ* facilities in the repository horizon to yield maximum information; the pilot and demonstration facilities can be operated in parallel with other underground operational activities. Other pilot or test activities can be carried out in surface facilities. To avoid suspicion that these *in situ* facilities are tactics intended only to accelerate waste emplacement, it is important that the public be informed of the purposes of, and results from, work in these facilities and that reversibility of any early stage can be demonstrated. If the implementer decides to use pilot, test, and demonstration facilities, the repository initial license application should contain provisions to implement these facilities.

4. **The repository implementer should ensure a continuous and active learning process.** During the decades of repository operation it is prudent, and it will be expected by the public, that the implementer continues to analyze whether initial safety assumptions remain valid and also continues to improve the system. To support this learning, repository programs should have:

- a broad, comprehensive, long-term science and technology program that continues throughout the lifetime of repository operations; is targeted and accountable, peer-reviewed, and of sufficient breadth to address key knowledge gaps, including those in social sciences; and also defines learning objectives for each stage;
- a monitoring program that collects scientific, technical, and societal data from appropriate sources; and
- a performance confirmation program that builds confidence in the ultimate performance of the repository, and focuses on data acquisition and modeling that is directly related to those issues on which the licensing and

[2]The committee acknowledges that pilot activities are unlikely to improve understanding of long-term repository behavior.

safety case are based, including performance assessment methodology testing.[3]

These three programs should be integrated but duplications should be avoided. The long-term science and technology program can address more general issues than the repository-focused experimental work in the test facility. Even so, the objective of this program is to improve repository operation and performance and to reduce the uncertainties, not just to perform open-ended science. Accordingly, the studies should be evaluated based on their progress toward filling identified knowledge gaps. The programs should be credible, transparent, and auditable.

5. **The repository program should integrate independent technical advice and stakeholder input to the maximum possible extent.** An essential component of continuous learning is proactively seeking stakeholder involvement rather than limiting involvement to public information meetings, which are often characteristic of Linear Staging procedures. A promising mechanism for stakeholder involvement, discussed in the National Research Council report *Understanding Risk* (NRC, 1996), is a structured, analytic-deliberative decision-making, process comprising iterative mutual learning among scientists, technical experts, and managers on the one hand, and representative stakeholders on the other (see Section 2.4). The success of such a process depends on two components: the proactive engagement of stakeholders throughout the repository program, and a structure that elicits stakeholder concerns and develops scientific or other means for addressing them. The implementer should encourage the establishment of a technical oversight group that also includes a social science component and is independent of the government to provide an independent technical analysis and to provide advice on the repository development program. Separately, a stakeholder advisory board consisting of representatives from institutional stakeholders and other stakeholder groups—such as local institutions, local and affected governments, universities, as well as representatives from industry, non-profit, and labor organizations—should provide additional input on stakeholder concerns, establish a venue for regular dialogue and consultation, and take part in Decision Points. The effectiveness of stakeholder involvement in the decision-making process should be evaluated as part of the learning activities of Adaptive Staging. Stakeholders' awareness of their role in the decision-making process may change their perceptions of decisions taken and reactions to new information.

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[3]In this context, performance assessment methodology testing emphasizes the application of performance assessment codes to natural systems to test how well these codes model natural systems.

6.11 Recommendations: U.S. program

The following recommendations are specific to the U.S. program and take into account the specific context and constraints that DOE is facing.

1. **DOE should adopt Adaptive Staging.** Consistent with international trends, two previous National Research Council committees have encouraged DOE to implement a flexible approach in its high-level waste repository development program (NRC, 1990, 2001). Some of the attributes essential for Adaptive Staging are already incorporated into the U.S. program; for example, stakeholders have access to a great amount of documentation and information. DOE is also in the process of introducing other changes in its program consistent with Adaptive Staging, the obvious examples being the increased emphasis on a potential pilot stage (see Appendix F, Section F.1.4), the development of a safety case approach (see Section 5.1.1), and demonstrating the feasibility of waste retrieval (see Section 5.1.3). However, DOE's program remains essentially Linear (Sections 5.2 and F.2).

   There are several actions that DOE could take to implement Adaptive Staging. For example, the safety case that DOE is planning to produce should include a description of safety arguments understandable by the general public that would be re-evaluated at all major Decision Points. The corresponding intentions and actions concerning the use of Adaptive Staging should be communicated to, and discussed with, stakeholders. DOE should also communicate the criteria it uses for judging the success of each stage and for deciding whether to change or even to reverse the course of actions.

   The committee believes that DOE could reduce its vulnerability to discovery of disabling error, improve the prospects of obtaining a license, and increase its opportunities to gain societal acceptance by wholeheartedly embracing Adaptive Staging.

2. **DOE should implement *in situ* pilot and test activities and should examine the possibilities for demonstration activities.** The committee recommends the introduction of a pilot stage designed to maximize systematic learning opportunities in the Yucca Mountain Project. However, DOE should make the purpose of these activities clear and understandable by stakeholders and the general public and should ensure that the appropriate licenses are received, if radioactive waste is used. The pilot emplacement stage,[4] which need last for only a few years, would consist of the initial emplacement of a fraction of the waste without the requirement of having the entire system (full-scale transport, storage, packaging, and disposal) in place. The learning gained from the pilot stage should help DOE to proceed expeditiously to full emplacement in the next stage unless significantly adverse information is gained or substantial system operation improvements are developed. Pilot trials are also recommended at the surface to assess,

[4]The committee envisions different pilot stages with different purposes during repository development; for instance, there could be a pilot stage to test closure, sealing, and long-term containment.

for example, waste packaging, transport, and canister welding. The decision on whether to conduct a large-scale *in situ* retrievability test should be made at an appropriate Decision Point.

DOE should expand its knowledge outside the bounds of the pilot stage by performing in parallel *in situ* test activities to develop improved confidence in waste isolation or in the overall performance of the repository. DOE should also examine, in collaboration with stakeholders, the potential benefits of reserving a fraction of the waste disposal area for demonstration purposes.

3. **DOE should set up an independent technical oversight group and a stakeholder advisory board.** The scientific work in the program must be—and must be recognized to be—subject to and responsive to independent input and review. The long-term science and technology program recently proposed by DOE should be given appropriate institutional status within DOE and should receive stable, long-term funding. Social science research should be included as an integral part of this program. The establishment of a system of independent peer review is important. Results of science and technology and monitoring programs should be published in peer-reviewed journals to the maximum extent possible. Care must be taken, however, not to delay the timely dissemination of data to program stakeholders and the general public through currently established mechanisms as well. Research activities should be relevant to Yucca Mountain and so justified. DOE should also establish an independent technical oversight group and a stakeholder advisory board (see Sections 4.2 and 5.1.3).

4. **Even if the U.S. program begins with a reduced-scale pilot stage, DOE should present a safety analysis and a safety case based on the full inventory.** If DOE decides to begin its repository program with a reduced-scale pilot stage, it should nevertheless develop both a safety analysis for the Nuclear Regulatory Commission and a safety case for stakeholders and the general public based on a full-inventory repository. A full-inventory safety analysis and a safety case are important to help establish confidence by regulator and the public in the ultimate safety of the complete repository system.

   The primary differences between the safety analysis and Adaptive Staging's safety case are that the safety case will be reviewed more often (i.e., at every Decision Point) and that it presents the description of the key safety arguments in a manner accessible to a wider audience. This accessible description is not necessary for the regulator, due to its technical expertise, who can make its judgment on repository safety based on the quantitative and qualitative compliance requirements in the regulations.

5. **DOE and the USNRC should work together (without compromising their independence) to ensure that the regulatory process enables the application of Adaptive Staging in the development of the Yucca Mountain Project.** The committee believes that the regulatory framework contains adequate flexibility to accommodate Adaptive Staging if the regulator supports this approach. DOE should take the initiative to demonstrate

the benefits of Adaptive Staging to the USNRC. DOE and the regulator should consider the potential interaction of Adaptive Staging and the regulatory process, including procedures for license amendments. In particular, the USNRC and DOE should have a common understanding of which changes, tests, and experiments can or cannot be made without advance regulatory approval. The USNRC has already identified some changes, tests, and experiments that can be made without advance regulatory approval and has provided decision criteria for these. The USNRC and DOE should consolidate and coordinate broad access to information and stakeholder participation, as well as evaluate opportunities to improve the current practices of DOE public hearings and USNRC licensing actions. Transparency and stakeholder oversight would ensure the independence of the regulating and regulated institutions.

6. **DOE should consider the impact of Adaptive Staging on the overall waste management system.** Before implementing Adaptive Staging for the entire repository system, DOE should ensure that there is an adequate understanding of the impacts of this approach for buffer storage at the repository and transportation requirements, for activities at reactors, for interim storage elsewhere, and for repository operations. In particular, the requirements for buffer storage at the repository site must be planned in advance. Buffer storage can relieve some pressure on DOE to accept commercial spent fuel as soon as construction authorization is granted.

7. **DOE should continue to promote a safety culture throughout the long duration of the Yucca Mountain Project.** Adaptive Staging is consistent with the considerable effort that has been devoted to developing a safety culture in the nuclear area (Sections 2.2 and 4.8). The current quality assurance standard for environmental management, ISO 14001, evaluating environmental management systems, has important principles in common with Adaptive Staging. The ISO standard 14001 (implemented at Waste Isolation Pilot Plant) could be an additional useful vehicle for enhancing the safety culture within the Yucca Mountain Project (see Section 4.8). ISO certification could be an important performance incentive for the DOE and its contractors and could be a valuable component in developing public trust by meeting a known and independently accepted standard for environmentally responsible management.

6.12 Concluding remarks

The committee debated at great length the originality of Adaptive Staging and the confidence with which it can advocate this approach as beneficial for waste disposal programs in the United States and elsewhere. To the first point, it is important to note that the term Adaptive Staging is used basically as shorthand for a collection of project management components, none of which is new or unique to this approach. Most of the components are to be expected in any major, well-managed project. The committee uses a new term (Adaptive Staging) to emphasize that *all* of the components should be applied simultaneously within a particular institutional culture that encourages continuous learning and that uses iterative review of system safety as the principal guiding mechanism.

In discussions about how strongly the committee could advocate the approach described, two opposing arguments recurred. The committee agreed that Adaptive Staging is a prudent approach, in line with the normal tenets of good project management, and can lead to program improvements. The committee recognizes, however, that these improvements will occur only if the implementer's organizational culture allows changes, and it acknowledges that this approach is untried.

These counterbalancing arguments lead to the cautious caveats applied to the committee's recommendations but should not detract from the consensus reached: because of the distinctive challenges faced in developing a geologic repository program (see Section 1.2.1), and the context in which these must be addressed (see Sections 2.5, 3.1, and 3.2), Adaptive Staging enhances the likelihood of program success.

References

ACNW (Advisory Committee on Nuclear Waste). 2002. Letter report from George Homberger, ACNW chairman, to R. A. Meserve, U.S. Nuclear Regulatory Commission chairman. Subject: Total System Performance Assessment and Conservatism. January 17. Washington, D.C.

AkEnd (Arbeitskreis Auswahlverfahren für Endlagerstandorte). 2002. DRAFT-Recommendations of the AkEnd. Committee on a Selection Procedure for Repository Sites. Safety Criteria and Site Selection Procedure for deep disposal of radioactive wastes. G. Arens. June. Federal Office for Radiation Protection.
Available at: http://www.akend.de/englisch/berichte/index_1024.htm.

Aryris, C. 1982. Reasoning, Learning and Action: Individual and Organizational. San Francisco, Calif.: Jossey Bass.

Bastide S., J. P. Moatti, J. P. Pages, and F. Fagnani.1989. Risk perception and the social acceptability of technologies: The French case. Risk Analysis 9:215-223.

Bechtel SAIC Company, LLC. 2002. Modular Construction System Evaluation. Pre-Decisional Study. TDR-CRW-SE-000023. Prepared for the U.S. Department of Energy, Office of Civilian Radioactive Waste Management, under contract number DE-AC28-01RW12101. August 2002. Las Vegas, Nev.: Bechtel SAIC.

Berman, P. 1980. Thinking about programmed and adaptive implementation: Matching strategies to situations. Pp. 205-227 in Ingram, H., and D. Mann, eds. Why Policies Succeed or Fail. London: Sage Publications.

Cha, Y. 2000. Risk perceptions in Korea: A comparison with Japan and the United States. Journal of Risk Research 3(4):321-332.

Curtis, C., C. Johnson, S. Rogers, D. Jackson, K. Rackham, G. Butler, T. Abbott, and S. Mitchell. 2001. The Role of Environmental Policy and Regulation: A Case for Modernisation. Cumbria, UK: Westlakes Research Institute, University of Manchester.

Cyert, R. M. and J. G. March. 1963. The Behavioral Theory of the Firm. Prentice-Hall. Englewood Cliffs, N. J. Prentice-Hall.

Depeche Meusienne. 2002. Bertrand Pancher Donne la Parole aux Meusiens. October 26. Page 5. Bar le Duc: Meuse Diffusion.

Dess, G. G. and D.W. Beard. 1984. Dimensions of organizational task environments. Administrative Science Quarterly 29:52-73.

DOE-OCRWM (Department of Energy, Office of Civilian Radioactive Waste Management). 2001a. Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program. DOE/RW-0533. Washington, D.C.: U.S. Department of Energy.
Available at: http://www.rw.doe.gov/tslccr1.pdf.

DOE-OCRWM. 2001b. Civilian Radioactive Waste Management System Total System Description Revision 02 (TDR-CRW-SE-000002). DOE/RW-0500. Washington, D.C.: U.S. Department of Energy.
Available at: http://www.rw.doe.gov/tsdkrb/tsdkrb.htm.

DOE-OCRWM. 2002a. Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-0250. February 2002.
Available at: http://www.ymp.gov/documents/feis_a/index.htm.

DOE-OCRWM. 2002b. Modular Construction System Evaluation. Pre-Decisional Study. TDR-CRW-SE-000023 REV 00. August 2002. Prepared by Bechtel SAIC. Washington, D.C.: U.S. Department of Energy.

DOE-SEAB (Department of Energy, Secretary of Energy Advisory Board). 1993. Earning Public Trust and Confidence: Requisites for Managing Radioactive Waste. Final Report of the Secretary of Energy Advisory Board Task Force on Radioactive Waste Management. November. Washington, D.C.: U.S. Department of Energy.
Available at: http://www.seab.energy.gov/publications/trust.pdf.

Dunlap, R. E., M. E. Kraft, and E. A. Rosa, eds. 1993. Public Reactions to Nuclear Waste: Citizens' Views of Repository Siting. Durham, N.C.: Duke University Press.

EDRAM (International Association for the Environmentally Safe Disposal of Radioactive Materials). 2002. The Management of Radioactive Waste; A Description of Ten Countries. By Lidskog, R., and A. Andersson. Örebro University. Orebro, Sweden: Research Center Man-Technology-Environment.

EKRA (Expert Group on Disposal Concepts for Radioactive Waste). 2000. Disposal Concepts for Radioactive Waste. Final Report. Report on behalf of the Federal Department for the Environment, Transport, Energy and Communication. January 31. Bern, Switzerland: Federal Office of Energy.

EKRA. 2002. Monitored Long-Term Disposal: A New Approach to the Disposal of Radioactive Waste in Switzerland. Report on behalf of the Federal Department for the Environment, Transport, Energy and Communication. Presentation at the NEC 2002 Scientific Seminar. October 7-9. Lille, France.

Emery, F. E. and E. L. Trist. 1965. The causal texture of organizational environments. Human Relations 18:21-32.

Englander, T., K. Farago, P. Slovic, and B. Fischhoff. 1986. A comparative analysis of risk perception in Hungary and the United States. Social Behaviour: An International Journal of Applied Social Psychology 1:55-66.

EPA (U.S. Environmental Protection Agency). 1999. Code of Federal Regulation, Title 40, Part 197. Environmental Radiation Protection Standards for Yucca Mountain, Nevada. August 27. 64 Federal Register 46976. Washington, D.C.: Government Printing Office.

EPRI (Electric Power Research Institute). 2001. Performance Confirmation for the Candidate Yucca Mountain High-Level Nuclear Waste Repository, Final Report-December 2001. Palo Alto, Calif.: EPRI.

Etzioni, A. 1967. Mixed scanning: A third approach to decision making. Public Administration Review (December): 385-392.

Flynn, J., P. Slovic, and C. K. Mertz. 1993. Decidedly different: Expert and public views of risks from a radioactive waste repository. Risk Analysis 13(6):643-648.

Forsberg, C. W. 1995. DUSCOBS: A Depleted-Uranium Silicate Backfill for Transport, Storage, and Disposal of Spent Nuclear Fuel. ORNL/TM 13045. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Forsberg, C. W. 2000. Effect of depleted-uranium dioxide particulate fill on spent nuclear fuel waste packages. Nuclear Technologies 131:337-353.

Foundations of Success. 2002. Adaptive Management: A Tool for Conservation Practitioners.
Available at: http://www.fosonline.org/whatwedo/adaptive_management.htm.

Galbraith, J. 1977. Organizational Design. Reading, Mass.: Addison-Wesley.

Holling, C. S. 1978. Adaptive Environmental Assessment and Management. New York: John Wiley & Sons.

HSK/KSA (Swiss Federal Nuclear Safety Inspectorate). 1993. Protection Objectives for the Disposal of Radioactive Waste. Regulatory Guidelines R-21 of the Swiss Federal Nuclear Safety Inspectorate. November. Bern, Switzerland: Swiss Federal Nuclear Safety Inspectorate.

IAEA (International Atomic Energy Agency). 1994. Siting of Geological Disposal Facilities, Safety Series No. 111-G-4.1. Vienna, Austria: IAEA.

IAEA. 1997. Regulatory Decision Making in the Presence of Uncertainty in the Context of the Disposal of Long Lived Radioactive Wastes. Third Report of the Working Group on Principles and Criteria for Radioactive Waste Disposal. IAEA-TECDOC-975. Vienna, Austria: IAEA.

IAEA. 2001a. Monitoring of Geological Repositories for High-Level Radioactive Waste. Tecdoc-1208. Vienna, Austria.

IAEA. 2001b. Measures to Strengthen International Co-operation in Nuclear, Radiation, Transport, and Waste Safety: Waste Safety. GOV/2001/31-GC(45/14). July 19. Vienna, Austria: IAEA.

INRA (European Co-ordination Office). 2001. Europeans and Radioactive Waste. Eurobarometer 56.2. April 19. Brussels, Belgium: European Commission.

Isaacs, T. 2002. Building Public Confidence in Nuclear Activities. Presented at the 2002 American Nuclear Society/International Congress on Advanced Nuclear Power Plants. June 13-14. Hollywood, Fla.
Available at: http://www3.inspi.ufl.edu/icapp/program/abstracts/1121.pdf.

ISO (International Organization for Standardization). 1996a. International Standard ISO 14001. Environmental Management Systems. Specification with guidance for use. First edition 1996-09-01. Reference number ISO 14001:1996(E). Licensed to the National Academies.

ISO. 1996b. International Standard ISO 14004. Environmental Management Systems. General Guidelines on Principles, Systems, and Supporting Techniques. First edition 1996-09-01. Reference number ISO 14004:1996(E). Licensed to the National Academies.

Itkin, I. 2000. Letter to Bruce Alberts, Chair, National Research Council, The National Academies asking for a committee to advise the Department of Energy, Office of Civilian Radioactive Waste Management on the Design and Operational Strategies for Repository Staging. October 19. Washington, D.C.

Jensen, K. A., C. S. Palenik, and R. C. Ewing. 2002. U^{6+} phases in the weathering zone of the Bangombé U-deposit; observed and predicted mineralogy. Radiochimica Acta 90:761-769.

Klinke, A., and O. Renn. 2002. A new approach to risk evaluation and management: Risk-based, precaution-based, and discourse-based strategies. Risk Analysis 22:1071-1094.

Konkel, R. M. 1990. Space Science in the Budget: An Analysis of Budgets and Resource Allocation in NASA, FY1961-1989. Center for Space and Geosciences Policy. May 1990. Boulder, Colo.: University of Colorado.

Kowalski, E. 2002. Negative Outcome of the Wallenberg Vote. Wallenberg Repository Cooperative (GNW) n-20922-prm-e2.doc. September 22. Wolfenschiessen, Switzerland.

La Porte, T. R. 1994. Large technical systems, institutional surprise and challenges to political legitimacy. Technology in Society 16(Dec.):269-288.

La Porte, T. R. and A. Keller. 1996. Assuring institutional constancy: Requisite for managing long-lived hazards. Public Administration Review 56(6):535-544.

La Porte, T., and D. Metlay. 1996. Facing a deficit of trust: Hazards and institutional trustworthiness. Public Administration Review 56(4):341-346.

La Porte, T. R. 2000. Institutional elements for long term stewardship in a nuclear age. Pp. 1-32 in Stewardship and the Design of 'Future Friendly' Technologies: Avoiding Operational Strain in Nuclear Materials Management at Scale. Final Report. LANL/UCB Stewardship Studies, 1998-2000. Berkeley, Calif.: University of California.
Available at: http://socrates.berkeley.edu:4050/regexp/part2.pdf.

Lee, K. N. 1993. Compass and Gyroscope. Integrating Science and Politics for the Environment. Washington, D.C.: Island Press.

Lee, K. N. 1999. Appraising adaptive management. Conservation Ecology 3(2):3.
Available at: http://www.consecol.org/vol3/iss2/art3.

Lindblom, C. E. 1959. The Science of Muddling Through. Public Administration Review (Spring):79-88.

Lindblom, C. E. 1965. The Intelligence of Democracy. New York: Basic Books.

Lipset, S. M., and W. Schneider. 1987. The Confidence Gap: Business, Labor and Government in the Public Mind. Baltimore, Md.: Johns Hopkins University Press.

Lundqvist, B. 2001. The Swedish Program for Spent Fuel Management. In Witherspoon, P.A. and G. S. Bodvarsson, eds. 2001. Geological Challenges in Radioactive Waste Isolation: Third Worldwide Review. LBNL-49767. Berkeley, Calif.: Berkeley Lab Press.

Makhijani, A. and Saleska S. 1999. The Nuclear Power Deception. U.S. Nuclear Mythology from Electricity "Too Cheap to Meter" to "Inherently Safe" Reactors. A report of the Institute for Energy and Environmental Research. New York: The Apex Press.

McCutcheon, C. 2002. Nuclear Reactions: The Politics of Operating a Radioactive Waste Disposal Site. Albuquerque, N.M.: University of New Mexico Press.

McKinley, I., P. Zuidema, S. Vomvoris, and P. Marshall. 2001. Swiss geological studies to support implementation of repository projects: Status 2001 and outlook. In Witherspoon, P. A. and G. S. Bodvarsson, eds. Geological Challenges in Radioactive Waste Isolation: Third Worldwide Review. LBNL-49767. Berkeley, Calif.: Berkeley Lab Press.

Mohanty, S. and B. Sagar. 2002. Importance of transparency and traceability in building a safety case for high-level nuclear waste repositories. Risk Analysis 22(1):7-15.

Murphy W. M. and R. B. Cadell. 1999 Alternative source term models for Yucca Mountain performance assessment based on natural analog data and secondary mineral solubility. Mat. Res. Soc. Conf. Proc. 556:551-558.

NEA (Nuclear Energy Agency). 1991. Disposal of Radioactive Waste: Can Long-Term Safety Be Evaluated? A Collective Opinion of the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency and the International Radioactive Waste Management Advisory Committee of the International Atomic Energy Agency, endorsed by the Experts for the Community Plan of Action in the Field of Radioactive Waste Management of the Commission of the European Communities. Paris, France: Organisation for Economic Cooperation and Development.

NEA. 1999a. Confidence in the Long-Term Safety of Deep Geological Repositories. Its Development and Communication. NEA 01809. Paris, France: Organisation for Economic Co-operation and Development. Available at: http://www.nea.fr/html/rwm/reports/1999/confidence.pdf.

NEA. 1999b. Geologic Disposal of Radioactive Waste: Review of Developments in the Last Decades. Paris, France: Organisation for Economic Co-operation and Development.

NEA. 1999c. The Role of the Nuclear Regulator in Promoting and Evaluating Safety Culture. Paris, France: Organisation for Economic Cooperation and Development.

NEA. 2001a. Joint NEA-IAEA International Peer Review of the Yucca Mountain Site Characterization Project's Total System Performance Assessment Supporting the Site Recommendation Process, Final Report. Available at: http://www.ymp.gov/documents/ymipr_a/toc.htm.

NEA. 2001b Reversibility and Retrievability in Geologic Disposal of Radioactive Waste. Reflections at the International Level. Paris, France: Organisation for Economic Cooperation and Development.

NEA. 2002. Establishing and Communicating Confidence in the Safety of Deep Geologic Disposal. Paris, France: Organisation for Economic Cooperation and Development.

NRC (National Research Council). 1957. The Disposal of Radioactive Waste on Land. Washington, D.C.: National Academy Press.

NRC. 1990. Rethinking High-Level Radioactive Waste Disposal: A Position Statement of the Board on Radioactive Waste Management. Washington, D.C.: National Academy Press.

NRC. 1996. Understanding Risk: Informing Decisions in a Democratic Society. Washington, D.C.: National Academy Press.

NRC. 1999. Environmental Management Systems and ISO 14001. Washington, D.C.: National Academy Press.

NRC. 2001. Disposition of High-Level Waste and Spent Nuclear Fuel. The Continuing Societal and Technical Challenges. Washington, D.C.: National Academy Press.

NRC. 2002a. Principles and Operational Strategies for Staged Repository Systems Progress Report. Washington, D.C.: National Academy Press.

NRC. 2002b. Making the Nation Safer: The Role of Science and Technology in Countering Terrorism. Washington, D.C.: National Academy Press.

NWPA (Nuclear Waste Policy Act). 1982. Available at: http://www.rw.doe.gov/progdocs/nwpa/nwpa.htm.

Nuclear Waste News. 2002. New OCRWM program will explore broad science, technology issues. Nuclear Waste News 22(50):491-492.

NWTRB (Nuclear Waste Technical Review Board). 2002. Letter report to Congress and the Department of Energy. January 24. Washington, D.C.

Nye County. 2002. Resolution stating the intent of Nye County to actively and constructively engage with the U.S. Department of Energy (DOE), the Administration, and Congress as the Yucca Mountain Project proceeds to final design, licensing, and implementation. Resolution No. 2002-22. April 16. Nye County Board of Commissioners. Nye County, Nev.

Pharr, S. J., and R. D. Putnam, eds. 2000. Disaffected Democracies. Princeton, N.J.: Princeton University Press.

Renn, O. In Press. The Challenge of Integrating Deliberation and Expertise: Participation and Discourse in Risk Management. In McDaniels, T. and M. Small, eds. Risk Analysis and Society: Interdisciplinary Perspectives. New York: Cambridge University Press.

Renn, O., T. Webler, and P. Wiedemann, eds. 1995. Fairness and Competence in Citizen Participation: Evaluating Models for Environmental Discourse. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Rosa, E. A., and D. L. Clark, Jr. 1999. Historical routes to technological gridlock: Nuclear technology as a prototypical vehicle. Research in Social Problems and Public Policy 7:21-57.

Rosa, E. A., and R. E. Dunlap. 1994. Nuclear power: Three decades of public opinion. Public Opinion Quarterly 58:295-324.

Rosa, E. A. 2001. Public acceptance of nuclear power: Déjà Vu all over again? Forum on Physics and Society. The American Physical Society. Spring 2001.
Available at: http://www.aps.org/units/fps/apr01/ap5.html.

Rosa, E. A. and G. Machlis. 2002. It's a bad thing to make one thing into two: Disciplinary distinctions as trained incapacities. Society and Natural Resources 15:251-262.

Sabatier, P. A. 1986. Top-down and bottom-up approaches to implementation research: A critical analysis and suggested synthesis. Journal of Public Policy 6(1):21-48.

Scott, W. R. 2003. Organizations: Rational, Natural and Open Systems, 5th ed. Upper Saddle River, N.J. Prentice Hall.

Slovic, P. 1987. Perception of risk. Science 236:280-285.

Slovic, P. 1993. Risk, trust, and democracy. Risk Analysis 13:675-682.

Steinbrunner, J. 1974. Cybernetic Theory of Decision, Part I. Princeton, N.J.: Princeton University Press.

Teigen, K. H., Brun, W., and Slovic, P. 1988. Societal risks as seen by the Norwegian public. Journal of Behavioral Decision Making 1:111-130.

Thompson, J. D. 1967. Organizations in Actions. New York: McGraw-Hill.

UKCEED (The UK Centre for Economic and Environmental Development). 2000. Workshop on the Monitoring and Retrievability of Radioactive Waste. A Report for Nirex prepared in association with the Centre for the Study of Environmental Change (CSEC) at Lancaster University. December 2. Manchester, United Kingdom.

USNRC (U.S. Nuclear Regulatory Commission). 2000. U.S. Nuclear Regulatory Commission Strategic Plan. NUREG-1614, FY2000-2005 Strategic Plan, September. Washington, D.C.: USNRC.

USNRC. 2002. Yucca Mountain Review Plan. NUREG-1804. Rev. March 2. USNRC.

Van Luik, A. 2001. Developing a Safety Case for Yucca Mountain. Presentation before the committee. December 19. Las Vegas, Nev.

Vira, J. 2001a. Taking it step by step: Finland's decision-in-principle on final disposal of spent nuclear fuel. Radwaste Solutions (September/October):30-35.

Vira, J. 2001b. Step-wise Decision-making in Trial: The Case of Finland. Paper presented at the 9th International High-Level Radioactive Waste Management Conference. 29 April–3 May, 2001. Las Vegas, Nev.

Walters, C., R. D. Goruk, and D. Radford. 1993. Rivers inlet sockeye salmon: An experiment in adaptive management. North American Journal of Fisheries Management 13:253-62.

Weart, S. 1988. Nuclear Fear: A History of Images. Cambridge, Mass.: Harvard University Press.

Webler, T., H., Kastenholz, and O. Renn. 1995. Public participation in impact assessments: A social learning perspective. Environmental Impact Assessment Review 15:443-463.

Wene, C. O., and R. Espejo. 1999. A Meaning for Transparency in Decision Processes. Pp. 404-421 in Proceedings of the VALDOR Symposium in the RISCOM Programme Addressing Transparency in Risk Assessment and Decision Making. June 13-17. Stockholm, Sweden: Karinta Konsult.

Williams, J. 2002. DOE's Vision of Staging. Presentation before the committee. June 10. Washington, D.C.

Witherspoon, P. A. and G. S. Bodvarsson, eds. 2001. Geological Challenges in Radioactive Waste Isolation: Third Worldwide Review. LBNL-49767. Berkeley, Calif.: Berkeley Lab Press.

Ziegler, J. P. 2002. Department of Energy Views on Safety Case and Safety Strategy for Repository Licensing. Presentation before the Nuclear Waste Technical Review Board. May 7. Washington, D.C.

Appendix A

Biographical Sketches of Committee Members

Charles McCombie, *Chair*, is an independent strategic and technical advisor to various national and international waste management programs. Formerly he was the scientific and technical director of NAGRA, the Swiss Cooperative for the Disposal of Radioactive Waste. He has 25 of years experience in the nuclear field, 20 of which are in radioactive waste management. His responsibilities have covered performance assessment, engineering and geologic investigations, and overall program direction. He has held positions as a research scientist with the U.K. Atomic Energy Authority and with the Swiss Federal Institute for Reactor Research. He has served on a number of committees advising national and international organizations on radioactive waste management issues. He is currently a member of the American Nuclear Society, Swiss Nuclear Energy Society, International Radiation Protection Association, Nuclear Advisory Committee of the Swiss Paul Scherrer Institute, and the National Research Council's Board on Radioactive Waste Management. Dr. McCombie received a B.S. in natural philosophy (physics) from the University of Aberdeen, Scotland, and a Ph.D. in physics (materials science) from the University of Bristol, England.

David E. Daniel (NAE), *Vice-Chair*, is the dean of the College of Engineering and professor of civil engineering at the University of Illinois. Professor Daniel received a Ph.D. in 1980 in civil engineering from the University of Texas at Austin and served on the faculty there until 1996. He has focused his work on the disposal of waste in landfills and on the cleanup of contaminated waste disposal sites with emphasis on clay liners and geosynthetic clay liners. He has written over 60 peer-reviewed journal articles and a similar number of conference proceeding papers. He won the American Society of Civil Engineers' (ASCE) two highest awards (Croes Medal and Norman Medal) for papers published in its journals, and has won ASCE's highest award (Thomas A. Middlebrooks Award) for a geotechnical paper published in its journals. Dr. Daniel has taught in more than 100 continuing education courses attended by about 15,000 scientists and engineers. He served on the Energy and Environmental Systems and Geotechnical Board of the National Research Council.

Robert M. Bernero received his B.A. from the University of St. Mary of the Lake (Illinois), a B.S. from the University of Illinois, and an M.S. from Rensselaer Polytechnic Institute. He retired in 1995 after 23 years of service with the U.S. Nuclear Regulatory Commission (USNRC), where he held numerous positions up to director of the Office of Nuclear Material Safety and Safeguards. Before joining the USNRC he worked for the General Electric Company in nuclear technology for 13 years. He served as a member of the Commission of Inquiry for an international review of Swedish nuclear regulatory activities, and he currently serves on the National Research Council's Board on Radioactive Waste Management. Currently, he consults on nuclear safety matters, particularly materials licensing and radioactive waste management.

Radford Byerly, Jr., retired as chief of staff of the U.S. House of Representatives Committee on Science and Technology after a distinguished career in academia and government, specializing in science policy and management. Dr. Byerly is co-author of several recent papers on federal R&D policy, including "Beyond Basic and Applied" (Physics Today, 1998) and "The Changing Ecology of United States Science" (Science, 1995). Among his many positions, Dr. Byerly has worked at the National Institute of Standards and Technology in the environmental measurement and fire research programs, and he was director of the University of Colorado's Center for Space and Geosciences Policy. He currently serves on the American Association for the Advancement of Science's Committee on Science, Engineering, and Public Policy and serves on National Science Foundation visiting committees and review panels. Dr. Byerly is a member of the Board of the Associated Universities for Research in Astronomy and previously served on the National Research Council's Committee on the Department of Energy's Office of Science and Technology's Peer Review Program. He received his Ph.D. in physics from Rice University.

Barbara L. Dutrow is the Adolphe G. Gueymard Professor of Geology and Geophysics at the Louisiana State University. Her field of specialization is metamorphic petrology with emphasis on thermal-chemical evolution of the crust, computational modeling of heat and mass transfer in fluid-rock systems, and fluid-rock interactions. Her research and teaching incorporate field, theoretical, experimental and computational methods to decipher Earth processes. She received her Ph.D. from Southern Methodist University in 1985. She was an Alexander von Humboldt fellow at Ruhr-Universität, Germany (1985–1987) and was a distinguished lecturer for Sigma Xi (1998–2000) and for the Mineralogical Society of America (1991–1992). Dr. Dutrow is a fellow of, and served as secretary for, the Mineralogical Society of America and is currently councillor for the society. She served on the Geochemical Society's Clarke Medal committee and is a member of the Geological Society of America, the American Geophysical Union and several other professional organizations. She served as Associate Editor for *Reviews of Geophysics* and for *The American Mineralogist*. She previously served on the National Research Council's Board on Earth Sciences and Resources.

Jerry M. Harris is a professor and chair of the Department of Geophysics at Stanford University. Dr. Harris received his B.S. in electrical engineering from the University of Mississippi, and both his M.S. and Ph.D. from the California Institute of Technology. He worked at the Communications Satellite Corporation, Exxon Production Research Company, and Standard Oil Production Company before joining the Stanford faculty. Dr. Harris is a graduate fellow of the Hughes Aircraft Company; a David and Lucille Packard Fellow; a former member of the Basic Energy Sciences Advisory Committee; and he earned a distinguished lecturer award from the Society of Petroleum Engineers. His research and teaching interests include seismic and electromagnetic wave propagation and imaging in complex geologic media. He is currently affiliated with the Society of Exploration Geophysicists, the Institute of Electrical and Electronics Engineers, the American Geophysical Union, and the Acoustical Society of America.

Thomas H. Isaacs has an extensive background in science policy and work experience directly relevant to the Yucca Mountain project. He is the director of Lawrence Livermore National Laboratory's (LLNL's) Office of Policy, Planning, and Special Studies. Mr. Isaacs is responsible for long-range strategic and institutional planning and conducts policy and technology studies for the laboratory. Before joining LLNL in 1996, he held a variety of positions within the U.S. Department of Energy, including executive director of the Department of Energy's Advisory Committee on External Regulation of DOE Nuclear Safety, director of Strategic Planning and International Programs, deputy director of the Office of Geologic Repositories for the department's radioactive waste program. Mr. Isaacs also served on the National Research Council's Committee on Building a Long-Term Environmental Quality Research and Development Program in the U.S. Department of Energy. Mr. Isaacs received a B.S. in chemical engineering from the University of Pennsylvania and an M.S. in engineering and applied physics from Harvard University.

Leonard F. Konikow has worked as a research hydrologist with the U.S. Geological Survey since 1972. He received a B.A. in geology from Hofstra University and an M.S. and Ph.D. from Pennsylvania State University. Dr. Konikow has published numerous papers and taught a variety of courses related to hydrogeology and groundwater modeling. He is a fellow of the American Geophysical Union and served as chairman of its Groundwater Committee and as hydrology program chairman. He received the M. King Hubbert Science Award from the National Ground Water Association (NGWA) in 1989 and was a member of the Board of Directors of the NGWA Association of Ground Water Scientists and Engineers. He is a fellow of the Geological Society of America (GSA), has been the society's Hydrogeology Division's Birdsall Distinguished Lecturer and recipient of its O.E. Meinzer Award, and served as chairman of the Hydrogeology Division of GSA. He served on the editorial board of *Ground Water* journal, as associate editor for *Water Resources Research*, and is currently the chairman of the U.S. National Chapter of the International Association of Hydrogeologists. He was also on the National Research Council's Committees on groundwater modeling assessment and the Waste Isolation Pilot Plant.

Todd R. La Porte is a professor of political science at the University of California at Berkeley. His fields of specialization are theories of public organization and administration and science, technology, and politics. Dr. La Porte teaches courses on public organization theory, administrative behavior, and technology and politics. His current research focuses on high-reliability organizations and the relationship of large-scale technical systems to political legitimacy. Dr. La Porte chaired the Secretary of Energy Advisory Board's Task Force on Radioactive Waste Management. He has served on the Board on Radioactive Waste Management and several other National Research Council committees. He was elected to the National Academy of Public Administration in 1985, but is no longer an active member. Dr. La Porte received his B.A. in social sciences and mathematics in 1953 from the University of Dubuque and received his M.A. in 1961 and his Ph.D. in 1963, both in political sciences from Stanford University.

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She recently served as chair of the Board on Earth Sciences and Resources' Rock Mechanics Committee. Dr. Long received an Sc.B. in engineering from Brown University, and an M.S. in geotechnical engineering and a Ph.D. in materials science and mineral engineering from the University of California, Berkeley.

Werner Lutze is a senior scientist at the Vitreous State Laboratory of The Catholic University of America, in Washington, D.C. In 2001, he retired from the University of New Mexico where he held a position as Professor of Chemical and Nuclear Engineering and as director of the university's Center for Radioactive Waste Management. He has over 25 years of research experience in materials science and geochemical issues relevant to the management of radioactive wastes, including selective mineral ion-exchange processes, repository near-field chemistry, waste form development, and trace analyses. He has published widely on weapons plutonium immobilization, waste disposal, and the chemistry of nuclear materials. Professor Lutze is a member of several professional organizations, including the Materials Research Society, the German Nuclear Society, and Sigma Xi. Dr. Lutze also served on the National Research Council's Committee on the Waste Isolation Pilot Plant.

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Wendell Weart has had an extensive 25-year history with the Waste Isolation Pilot Plant as the project's principal science advisor. Recently retired as a Sandia National Laboratories fellow, he has over 40 years of expertise in the fields of geotechnical and radioactive waste management research. Dr. Weart's research focused on the physical effects of underground explosions and on nuclear waste disposal in geologic media. He was a geophysicist with the Ballistics Research Laboratory and Sandia National Laboratories and manager of nuclear waste systems at Sandia before becoming a Sandia senior scientist and a Sandia fellow concentrating on nuclear waste disposal issues. He is a member of the American Association for the Advancement of Science and of the American Geophysical Union. Dr. Weart earned a B.A. from Cornell College in geology and mathematics and a Ph.D. in geophysics from the University of Wisconsin.

Appendix B

Information-Gathering Meetings

Below is a list of presentations the committee received during information-gathering meetings. These were open to the public and included opportunities for public comment.

B.1 Meeting 1: June 27-29, 2001, Washington, D.C.

- *Welcome and Presentation of the Study,* C. McCombie, committee chair.
- *Sponsor's Hopes and Expectations for This Study,* L. Barrett, Department of Energy—Office of Civilian Radioactive Waste Management (DOE-OCRWM).
- *Overview of the U.S. Yucca Mountain Project,* J. Williams, DOE-OCRWM
- *Perspective of the U.S. Environmental Protection Agency (USEPA),* F. Marcinowski, USEPA.
- *Recent Findings from U.S. Public Opinion Surveys on Nuclear Energy Issues,* Mark Richards, Bisconti Research, Inc.
- *Views from the Institute for Energy and Environmental Research (IEER),* A. Makhijani, IEER.
- *Perspective from the U.S. Nuclear Regulatory Commission (USNRC),* W. Reamer, USNRC.
- *Perspectives on Policy Issues and Overview of Step-Wise Approaches in Foreign Countries,* C. McCombie, committee chair.
- *Perspectives of the Nuclear Energy Institute (NEI),* S. Kraft, NEI.
- *Risk, The Public, And Public Agencies,* W. Freudenburg, University of Wisconsin-Madison.
- *Institutional Challenges for High-Reliability Systems across Many Operational Generations,* T. LaPorte, University of California, Berkeley.

B.2 Meeting 2: September 5-7, 2001, Washington, D.C.

- *Opening Remarks from The U.S. Department of Energy,* L. Barrett, DOE-OCRWM.
- *Staging in Repository Systems: Current Views on Staging from the Nuclear Community.* C. Pescatore, Nuclear Energy Agency-Organization for Economic Co-operation and Development (NEA-OECD).
- *Staging: Institutional and Organizational Aspects,* J. Ahearne, Sigma Xi.
- *Staging: Public Interaction and Acceptance Aspects,* J. Flynn, Decision Research, Inc.

- *Staging: Policy, Legal, and Regulatory Aspects,* M. Federline, USNRC.
- *Staging: Can Science Develop Confidence?* N. Oreskes, University of California, San Diego (UCSD).
- *Application of Staging in Sweden and Finland,* T. Eng, Svensk Karnbranslehantering (SKB), Sweden.
- *Application of Staging in Switzerland,* P. Zuidema, National Cooperative for the Disposal of Radioactive Waste (NAGRA), Switzerland.
- *Application of Staging in France,* Y. Le Bars, National Radioactive Waste Management Agency (ANDRA), France.
- *Application of Staging in the United States: Waste Isolation Pilot Plant,* G. Dials, USEPA.
- *Staging in NASA Missions,* S. Johnson, University of North Dakota.
- *Staging the Introduction of a Genetically Modified Organism,* E. Hallerman, Virginia Polytechnic Institute.
- *Monitoring of Repositories: Views of the International Waste Management Community,* A. Bonne, International Atomic Energy Agency (IAEA).
- *Environmental Monitoring,* L. Everett, The IT Group.
- *Critical Question: Does Monitoring Really Increase Safety and Acceptability?* T. Weinmann, CTL Group.
- *Reversibility and Retrievability: Views of the Waste Management International Community,* B. McKirdy, National Inventory of Radioactive Waste (NIREX), United Kingdom.
- *Critical Question: Do Economic and Safety Costs of Retrievability Justify Gains?* P. Zuidema, NAGRA.
- *Spent Nuclear Fuel and High-Level Waste in Repository Staging,* W. North, Northworks, Inc.
- *Discussion: Lessons Learned from the Workshop and Opportunity for Public Comments.* C. McCombie, committee chair.
- *Workshop Concluding Remarks,* C. McCombie, committee chair.

B.3 Meeting 3: December 17-19, 2001, Las Vegas, Nevada

- *Welcome and Presentation of the Committee,* C. McCombie, committee chair.
- *Performance Confirmation and DOE's Monitoring Plans,* W. Boyle, Department of Energy-Yucca Mountain Project (DOE-YMP).
- *Geophysical Monitoring: Models, Uncertainties, Safety Concerns,* J. Brune, University of Nevada, Reno.
- *Conceptual Models in Hydrogeological Studies,* P. Hsieh, U.S. Geological Survey (USGS).
- *Hydrological Monitoring at Yucca Mountain,* L. Lehman, independent consultant.
- *Focus on Non-Technical Uncertainties,* Allen Benson, DOE-YMP Institutional Affairs; R. Loux, State of Nevada Representative; J.R Taguchi, Chair of the Nye County Board of Commissioners; K. J. Phillips, mayor of Caliente, Nevada.
- *Panel Discussion on the Role of the State Educational System in the Yucca Mountain Project,* K. Stetzenbach, director of the Harry Reid Center of the University of Nevada, Las Vegas; D. Shafer, Desert Research Institute.
- *The View of an Independent Organization,* S. Snyder, Shundahai Network.

- *DOE's Safety Case,* A. Van Luik, DOE-Yucca Mountain Project.
- *U.S. Nuclear Regulatory Commission (USNRC) Update on 10 CFR 63,* T. McCartin, USNRC.
- *Long-Term Research and Development Needs and Staging,* W. Glassley, Lawrence Livermore National Laboratory; J. Price, Nevada Bureau of Mines and Geology.

B.4 Meeting 4: June 10-11, 2002, Washington, D.C.

- *DOE's Vision of Staging,* M. Chu and J. Williams, DOE-OCRWM.
- *State of Nevada's Feedback on Committee's Progress Report,* S. Frishman, State of Nevada.
- *Nuclear Energy Institute's Feedback on Committee's Progress Report,* S. Kraft, NEI.
- *USNRC's Feedback on Committee's Progress Report,* M. Federline, USNRC.
- *Status on Repository Design—Geotechnical Considerations,* M. Board, Bechtel Science Applications International Corporation (Bechtel-SAIC).
- *DOE's Flexible Repository Design,* W. Stroupe, Bechtel-SAIC.
- *DOE's Long-Term Science Plan for Yucca Mountain,* S. Brocoum, DOE-Yucca Mountain Project.

B.5 Meeting 5: August 12, 2002, Berkeley, California

- *Yucca Mountain Program Overview,* M. Chu, DOE-YMP.

Appendix C

NASA's Apollo and Space Station Programs

Both case studies considered here are examples of Linear Staging: the National Aeronautics and Space Administration's (NASA's) Apollo Program and its International Space Station (ISS) Program. The cases are compared to the criteria given in Chapter 2 (Section 2.5) and discussed as to whether the Linear approach succeeded. To summarize the lessons of the examples: the Apollo example shows that when criteria for Adaptive Staging are not met, a Linear approach can work well. The Station example shows that when the criteria call for Adaptive Staging, a Linear approach can fail badly: when new information forced NASA to change its design (i.e., to adapt), it responded with a new design (i.e., a new Linear approach) that soon had to be changed again.

C.1 NASA's Apollo Program[1]

Does this program meet the 12 Adaptive Staging criteria (see Section 2.5)? It did for two criteria.

C.1.1 Matching criteria to the Apollo Program

Only Criteria 1 and 2 were met. The project was unprecedented. Ten criteria were not met. Criterion 2: The project's goals were not controversial; there were no dissenting voices when President John F. Kennedy made the commitment to go to the Moon. Criterion 3: The implementing methods (experimental space launches) were noncontroversial. Criterion 4: The properties of the environment, outer space and the surface of the Moon, were somewhat known. The environments, although not fully understood, received substantial scrutiny during unmanned explorations that preceded the Moon landing. Further, ongoing space exploration missions were finding no substantial surprises.

Criteria 5 and 6: Outputs could be correlated with inputs. The project's consequences developed quickly: the public failures of early (unmanned) launch vehicles in the Mercury Program resulted in highly visible corrective actions. Rocket flights to the Moon gathered prestige for the United States. Criterion 7: Although there were risks to the astronauts, the public did not perceive any personal risk. Criterion 8: Financial resources were generous and a skilled workforce was available. Criterion

[1] Two general references for this case are Logsdon's *The Decision to Go to the Moon: Project Apollo and the National Interest* (1970) and Roland's *The Lonely Race to Mars: The Future of Manned Spaceflight* (1992)

9: The public perceived a geopolitical crisis if the Soviet Union were the first to claim the lunar surface.

Criterion 10: NASA's openness about failures and the eventual success of the Mercury and Gemini Programs, even though limited to Earth-orbit, built societal confidence in NASA. Criterion 11: The public did not want to participate in the program's decisions; they observed the programs in the media and facing no personal hazard from it, were happy to leave decisions to "rocket scientists." Criterion 12: NASA, although a new agency, was a stable institution with broad political support. The highly visible successes of Mercury and Gemini solidified NASA's support and readied the agency for Apollo.

C.1.2 Determining program success

This program was successful. The program's goal was essentially geopolitical, to demonstrate the prowess of the United States, and this it did on schedule. It achieved the goal by accomplishing what President John F. Kennedy had promised in 1961: to land a man on the Moon within a decade. The Apollo Program is a successful example of Linear Staging.

The program received generous financial resources and political support; cost overruns were not a factor in determining success. Supporters could tolerate a few years of overruns; indeed, annual program costs peaked two years before the Moon landing, and their decline encouraged continued support (Konkel, 1990).

Success was a singular event. As soon as the lunar module landed on the Moon and returned safely to Earth, Apollo was a success by definition. That there were failures cannot be discounted. Three astronauts died in a fire during tests on the ground. Apollo 13 failed to land on the Moon, and barely returned to Earth safely. But these failures did not undermine the program's overall success.

C.2 Linear Staging: NASA's International Space Station Program

Does this program meet the 12 Adaptive Staging criteria (see Section 2.5)? It did for seven criteria.

C.2.1 Matching criteria to the International Space Station

Criteria 1, 2, 3, 5, 6, 8, and 12 were met. Criterion 1: The program is unprecedented. Criterion 2: There is no clear agreement on the project's goal(s). Criterion 3: The many redesigns of the station demonstrate not only disagreement about the goal(s) but also controversy over the implementing methods. Criterion 5: The history of redesigns suggests that outcomes do not have a known dependence on inputs, at least in the development process. Criterion 6: The program has been so long in development that there are as yet no consequences to assess.

Criterion 8: Financial resources are limited and Congress continues to threaten the program by further limiting financial resources. Criterion 12: Although NASA as a whole is a relatively stable institution, Congress mandated that NASA reorganize the program several times.

Criterion 4 is not met: The technical properties of the environment are now well known. Criterion 7 is also not met since there is no perceived hazard associated with the existence of an international space station. Criterion 9 is not met: the realization of an international space station is not critical. There is no need for action.

Whether Criteria 10 and 11 are met is debatable. Criterion 10: distrust of NASA has increased because of problems and failures in (1) the Shuttle Program (including the Challenger accident, cost overruns, and delays) and (2) the Station Program itself (failure to fulfill promises to foreign partners, cost overruns, delays, and redesigns). Criterion 11: The public does not expect to participate in program decisions, but its representative, the Congress, is restive due to cost overruns, delays, and reductions in performance.

The "score" is: seven criteria for using Adaptive Staging, three for not using Adaptive Staging, and two indeterminate. The score suggests that it would be useful for NASA to move away from its use of a Linear and predetermined approach. At least in the development phase Linear Staging has not succeeded because of many cost, performance, and schedule problems as described below.

C.2.2 Determining program success

NASA's Space Station Program offers a clear, if disappointing, example of the dangers of applying Linear Staging to managing a complex, first-of-a-kind program. "The International Space Station at Risk" was the title of a recent editorial in Science (Young, 2002), which covered only the recent problems of this program. The point of the following account[2] of programmatic failure is that a Linear approach can be very unsuccessful when criteria indicate that Adaptive Staging might be better. In such a case an Adaptive approach could be faster, cheaper, and more effective.

In the early 1980s NASA spent hundreds of millions of dollars gathering information in preparation for designing the space station. This was the first step in NASA's Linear approach to developing a space station. Much of the effort went to determining the needs of potential users of the station, such as scientists doing experiments in zero gravity. Most of the science needed to build the station was known, but the engineering challenges were great. NASA also relied on its experience in other crewed laboratories in space (e.g., the Skylab Program and the shuttle-borne Spacelab).

In 1984, President Ronald Reagan directed NASA to build a station within a decade. Later that year, NASA revealed its design (i.e., the end point of the predetermined path) for a very capable, permanently occupied station, including research facilities at the station and two free-flying automated platforms for research and Earth observation. The cost was $8 billion (this design would have generated electrical power, one rough index of capability, of 75 kilowatts). The next several years saw struggles to contain costs and meet contingencies. Redesigns, cost estimates, and surprises chased each other: for example, the 1986 Challenger accident

[2]This appendix draws heavily on the work of Marcia S. Smith, an analyst at the Congressional Research Service, Library of Congress, who has followed NASA programs for years and the Space Station program from its inception (Smith, 2001, 2002). An additional source of information was the report of a blue-ribbon committee on the space station, the "Young Committee" (IMCE, 2001). The blue ribbon committee was appointed by NASA at the urging of the Office of Management and Budget to study the latest space station cost overruns, their causes, consequences, and cures.

caused the program to add a "lifeboat" for emergency return of the crew. The automated platforms (see below) were deleted as were other capabilities (e.g., electrical power was reduced). By 1990, the cost estimate was $38.3 billion for a different, much less capable station.

NASA redesigned again, and in 1991 presented a still less capable $30 billion design. Congressional concern over cost overruns, delays, and reduction of capability led the House Appropriations Committee to delete all funds for the station from the NASA appropriations bill in what was to be the first of 22 congressional votes to kill the program. The funds were restored by the full House. This is evidence of a controversial program. In 1993, Russia joined existing international partners Europe, Japan, and Canada in the program. The station was again redesigned, now as the International Space Station, with a cost of $17.4 billion of additional funds. Russia committed to build and launch some elements of the station. At this point $11.2 billion had been spent on the program and nothing had been launched, although some parts were built.

The costs continued to grow, and the station design continued to change, always becoming less capable. Different cost estimates are hard to compare directly, because they include different items: some include the costs of shuttle launches necessary to put the station in orbit; some include the salaries of NASA civil servants; some do not.

In November 2001, an ISS Management and Cost Evaluation Task Force chaired by Thomas Young released a status report on the station. By now a permanently occupied station with a crew of three was in orbit, partially equipped for research, with the station producing 20 kilowatts of electrical power. The Young committee found that there was little technical risk in designing and developing the balance of the planned station; in other words, the technical design problems were largely solved. Despite having this source of technical uncertainty removed, the committee found that NASA still had no rigorous estimate for the cost of finishing the ISS. The task force found that the estimated cost of completing the station had grown from $17.4 billion to something over $30 billion, and was still growing. Neither the Administration nor Congress want to pay what it will cost to finish the station, but unless it is finished the program will not be able to deliver the promised capabilities to its international partners. At this writing (2003), the issue is not yet resolved but the station may stay with a crew of only three. Smith (2001) explains the many changes made in the program, how the station's capability has varied over time, and how costs have grown.

For example, the $8 billion estimate from 1984 was only for research and development and was expressed in FY1984 dollars. In the FY1988 NASA authorization bill, however, Congress directed NASA to include other costs in the estimate, including, for example, marginal shuttle launch costs during assembly; tracking and data services; the since canceled flight telerobotic servicer; and ground test facilities. Subsequent estimates for the Freedom Program, therefore, included those additional items. Also, NASA began expressing the estimates in "real year dollars," meaning that funding shown for previous years is actual costs, while estimates of future-year funding are adjusted for expected inflation. For the ongoing ISS Program, NASA returned to the practice of not including launch costs, for example, but includes the costs of science experiments, which were not included in cost estimates for Freedom.

Another complication when comparing the original $8 billion cost with today's estimates is that the original design was not only for an occupied base where astronauts would live and work, but also for two automated platforms (one in an orbit near the space station for scientific experiments and one in an orbit around Earth's poles for Earth observations). Other content changes were made. Thus, the $8 billion was an estimate for a much more capable set of space facilities than the occupied base being built today.

Different cost estimates from FY1985–2000 cover work to complete different stages, either "assembly complete" or "permanent human occupancy", and do not include operational costs past those dates. "Assembly complete" is the stage at which the space station would be completely assembled. "Permanent human capability" (PHC) was an earlier stage NASA used for budgeting and scheduling purposes beginning with the March 1991 redesign through the end of the Freedom Program in 1993. PHC denoted when a crew could remain aboard the station year-round without the space shuttle attached. NASA explained that it was using PHC instead of assembly complete to illustrate that the space station would continually evolve in an undefined and unbudgeted follow-on phase, and hence would not be "complete" at a particular point in time. With the advent of the ISS Program, NASA returned to the practice of using an assembly-complete date; however, in FY2000 NASA added another benchmark, "development complete," to denote when a six- or seven-person research capability would begin. (Although NASA said ISS would accommodate six people, for several years it has been suggested that seven could be accommodated if an appropriately-designed crew return vehicle were available.) For FY2000 and FY2001, NASA listed both dates with accompanying schedule and cost estimates (see the definition of Linear Staging, Section 2.1).

The details of the changes in the Space Station Program over its life are given in testimony by Marcia Smith (Smith, 2001, 2002). Smith identifies six major program changes from 1984 to 1993, although other analysts may cite a higher number, indicating unclear goals (Smith, 2001).

NASA's recent proposal to curtail space station construction once the "U.S. core" is completed is a further change causing $4 billion in cost growth in the ISS budget. Because Congress has not yet approved NASA's decision, this potential program change is formally "under discussion." If NASA proceeds in this direction, three U.S. elements will not be built until additional funding is available—the habitation module, crew return vehicle (CRV), and propulsion module. Concern has been expressed that if the CRV is not built, the probable reduction in crew size, from six or seven to three, will limit how much scientific research can be conducted because about 2.5 crew members will be needed simply to maintain the station.

In summary, the Apollo Program is a successful example of Linear Staging whereas the ISS Program is not, at least to date (2003). The challenges of NASA's space programs are obviously very different from those of a geologic repository program. Nonetheless, these programs represent first-of-a-kind, complex, and long-term projects that serve to illustrate the application of the criteria defined Section 2.5.

References

IMCE (International Space Station Management and Cost Evaluation). 2001. Report by the International Space Station Management and Cost Evaluation Task Force to the NASA Advisory Council. November 1, 2001. Available at ftp:// ftp.hq.nasa.gov/pub/ pao/reports/2001/imce.pdf

Konkel, R. M. 1990. Space Science in the Budget: An Analysis of Budgets and Resource Allocation in NASA, FY1961–1989. May. University of Colorado, Boulder: Center for Space and Geosciences Policy

Logsdon, J. M. 1970. The Decision to Go to the Moon: Project Apollo and the National Interest. Cambridge, Mass.: MIT Press.

Roland, A. 1992. The lonely race to Mars: The future of manned space flight. Pp. 35-49 in Space Policy Alternatives, R. Byerly (ed.). Boulder, Colo.: Westview Press.

Smith, M. S. 2001. NASA's Space Station Program: Evolution and Current Status. Testimony before the House Science Committee, 107th Congress, Washington, D.C., April 4, 2001. Library of Congress. Serial 107–8107-8. Washington, D.C.: Government Printing Office.
Available at: http://www.hq.nasa.gov/office/pao/History/smith.htm.

Smith, M. S. 2002. Space Stations. IB93017. CRS Issue Brief for Congress. April 29. Washington, D.C.: Congressional Research Service, Library of Congress.

Young, L.R. 2002. The international space station at risk. Science 296:429.

Further Reading

Brunner, R. D., R. Byerly, Jr., and R. A. Pielke Jr. 1992. The future of the space station program. Pp. 199-222 in Space Policy Alternatives, R. Byerly (ed.). Boulder, Colo.: Westview Press.

Appendix D

Staging from an International Perspective

This appendix first examines how the various attributes the committee has used to characterize Adaptive Staging have been reflected in national disposal programs around the world. It can be shown that many of the individual attributes describe the work undertaken in different countries. Nevertheless, there have been numerous setbacks experienced by national programs. The second part of the appendix examines these negative outcomes and assesses whether the situation might have been different with full use of the Adaptive Staging approach.

D.1 The characteristics of Adaptive Staging and their application in national programs

From the beginning it has been apparent that geologic disposal must be implemented in a phased manner. Early guidance in the International Atomic Energy Agency (IAEA) publication series, for example, noted the list of phases or steps recommended for implementation, with particular emphasis on the siting process itself. Proceeding in stages toward final operation and closure of a deep repository, as recommended in this report, is a concept with a long history (IAEA, 1994).

The iterative use of performance assessments or safety analyses to guide the staging process is also a concept with a long history. Again, guidance documents from international organizations such as the IAEA and the Nuclear Energy Agency (NEA) illustrate this well. In the United States, iterative total-system-performance analyses (TSPA's) became a working tool later than in some European programs. TSPA played an important role in both the Waste Isolation Pilot Plant (WIPP) and the Yucca Mountain programs.

As is emphasized in this report the entire repository development program should be advanced in a system with a strong safety culture. The overriding concern is to ensure adequate safety throughout, from short-term operations through to the very long-term post-closure phase. The following section provides an outline of how this attention to safety issues has influenced national repository programs.

D.1.1 The overarching goal–ensuring safety

The principle is that options should be chosen with a high weighting on increasing repository safety and enhancing confidence in the safety case. The former aspect has always been emphasized—or even overemphasized—in national programs; the importance of the latter (confidence in the safety case) of this requirement was, however, initially underestimated.

Extensive lists of safety–oriented geologic siting criteria were produced (e.g., in 10 CFR Part 60). In France, site-screening criteria before 1991 covered purely geologic safety aspects. Japan started by looking only at the selection of rock types suited to providing safety. The relatively similar rock types available in Sweden and Finland meant that these national programs could focus earlier on other criteria determining the suitability of a site. Despite being based on similarly very old and very extensive crystalline rock formations, this factor did not play the same role in the Canadian program. Canadian government experts, in the major review of the generic phase of a multiyear program, concluded that technical safety alone was insufficient and that demonstration of confidence in safety was equally important.

The importance of being able to demonstrate repository safety also become clear in other programs in which siting choices were sometimes made that led to selection of candidate sites with complex geology or were difficult to investigate. One example was in Switzerland, where the three candidate sites originally chosen for geologic disposal of low and intermediate-level waste (L/ILW) were in complex, high-topography, pre-Alpine regions. This was, in large measure, because the selection process put a high premium on the availability of existing geologic data and little weight on the ease of understanding the site and its behavior. In the United Kingdom, the Sellafield site was selected largely on economic grounds, with the assumption that demonstrating safety would be an easily solved problem (Dodgson et al., 2001). This assumption led to increasing problems culminating in the failure of the Nuclear Industry Radioactive Waste Executive (NIREX) program at the U.K. public hearings in 1995. In France, the government scientific review group, *the Commission Nationale d'Evaluation* (CNE), blocked plans to investigate a proposed granite site because the structures were thought to be too complex for reliable characterization.

In the design of engineered barrier systems (EBS), the advantages of simple, easily understood systems that could enhance confidence were not immediately recognized. The Swedish program, with its choice of a canister made from the natural, thermodynamically stable material, copper, and a surrounding buffer of naturally-occurring bentonite clay (Lundqvist, 2001), was a leader in stressing this respect. Designs for engineered barrier systems using complex, multilayer containers, sometimes with inclusion of tailored components enhancing retention of specific radionuclides, have been proposed but have not become the reference choice in major programs. The very simple, rather idealized reference designs are, however, being reviewed as implementation approaches to ensure that they are practicable and allow safe quality-assured remote handling during emplacement.

As national disposal programs have moved ahead, there has not only been a growing realization of the importance of confidence in safety, there has also been increasing acknowledgement that residual uncertainties will remain and that decisions must be made in the face of these uncertainties (NEA, 1999). Performance assessment was recognized by the technical community as a valuable tool for examining the level of safety and its uncertainty. After a period of emphasis on the quantitative results of analyses, the concept of a safety case that includes broader evidence of the reliability of safety estimates was widely adopted in repository programs worldwide. In many programs (e.g., Sweden, Finland, Switzerland, Japan, and the United States), iterative performance assessments and/or reviews of the broad safety case have become a standard input to decisions in a staged repository development.

There is a long history of safety-case-driven stepwise procedures leading toward geologic disposal. Where, then, do the proposals of the committee for Adaptive Staging differ from what has been happening? The commonalities and differences can be illustrated by considering the attributes of Adaptive Staging as described by the committee:

- commitment to systematic learning;
- flexibility, including reversibility;
- auditability, transparency, integrity; and
- responsiveness.

D.1.2 Commitment to systematic learning

All major projects must expect to adapt to new knowledge as they advance. The characteristic of Adaptive Staging is that this process is encouraged and, as far as possible, planned in advance. To achieve this, active measures must be taken to seek new knowledge, and an organizational culture must be established that is open to new information and is prepared to act on it. To gather new data and increase understanding, almost all repository programs begin with a research and development program. In some cases (e.g., in the United States, Sweden, Canada, France) a broad program began early. Some other, often smaller countries (e.g. Switzerland, Belgium, and Finland) also began early, but they tried to select research and development that complemented rather than duplicated other efforts. Perhaps the greatest omission in all cases was caused by the concentration on pure technical issues and the underestimation of the need for parallel efforts in the social sciences.

At a more project-specific level, various countries recognized early the potential of underground test facilities to encourage systematic learning. The pioneering underground research laboratories were in Sweden (Stripa and, later, Aspo), Switzerland (Grimsel), Belgium (Mol), and Canada (Whiteshell). Other countries, such as France (Fanay Augere), the U.S. (Climax), and Japan (Tono and Kamaishi), followed suit. Some countries (e.g., Spain and the United Kingdom) failed to get the public acceptance needed for implementing an underground research laboratory. Many of the laboratories developed into international research facilities allowing collaboration among scientists from different nations. The U.S. Climax facility was closed, but the geologic repository at WIPP is encouraging others to participate in joint research projects.

In the area of site selection and characterization, effort has gone into planning how best to systematically acquire the knowledge needed to choose suitable sites and to understand their characteristics; and have attempted a process of narrowing lists of candidate sites to the most promising sites; most programs have a staged site-investigation process, which uses earlier findings to shape later studies. A few nations have attempted to omit this phase or to shorten it for cost reasons. This has inevitably led to controversy. For example, Germany chose the Gorleben site without a transparent justification. The United States and the United Kingdom short circuited a planned high-level waste selection process based on comparing results from more than one site and moved directly to a single preferred option (Yucca Mountain and Sellafield, respectively).

As information-gathering tools further the way toward realization of geologic repositories, the value of pilot facilities at the chosen site has been recognized in some programs. Sweden was the first country to propose a reversible pilot disposal phase; Switzerland has also proposed a pilot stage. The French program is undertaking underground investigations, currently at one potential deep disposal site and possibly at two, which will likely lead to pilot studies for disposal.

Belatedly, some countries have realized the importance of encouraging a parallel learning process in the social sciences. Following the dramatic failure of the technocratically managed Sellafield disposal project, the British government moved to the other extreme and launched an extremely wide and lenghty public consultation process. Similarly in Canada the total collapse of a 15-year technical program intended to lead to a decision for progressing from a generic to a site-specific phase has led to almost all emphasis shifting to the societal problems associated with disposal projects. In both cases, there has been a clear stepping back from the commitment to find a geologic disposal solution and a political readiness to question all previous decisions. It can, however, be asked how much of this openness is attributable to proposed approaches that may also lead to long non-controversial discussion phases that cause little discomfort to politicians.

The above summary illustrates the many strategic choices that have been made and the specific projects implemented with the goal of encouraging systematic learning about the repository system. There is less agreement on whether repository implementers have shown sufficient readiness to act with enough flexibility on new information gained. The question of whether an open mind has been kept, with all possible future options being reviewed in light of the knowledge gained, or whether implementers seek a minimum "technical fix" that will enable them to avoid radical change or even reversal, remains open for discussion.

D.1.3 Flexibility with multiple choices, including reversal

The reversal attribute has grown enormously in importance over the past several years. Geologic disposal has been tacitly acknowledged to be reversible for very long times, given sufficient available time and resources. The United States had at an early stage of its program a requirement for retrievability (see Appendix F). However, explicit demand for demonstration of reversibility in general and retrievability of emplaced wastes, in particular, has increased. Several nations have reversibility or retrievability over long or indefinite times built into their legal or regulatory framework (e.g., France, Finland, United States, Switzerland, and the Netherlands). In recent years major international meetings have been devoted to the topic, and international bodies have published documents on the subject of retrievability (Euratom, 2000; KASAM, 2000; NEA, 1995).

The main reason for the increased emphasis on reversibility has been that the technical community is listening to societal demands more closely. Originally the tendency was for the technical experts to argue that disposal would be implemented only if performance assessments had demonstrated such a high-level of confidence that the need for retrieval was inconceivable (see for instance IAEA, 1995). This trust in the reliability of scientific analysis of long-term behavior was not, however, shared by the general public; hence, efforts to show that retrievability was indeed possible were increased. More fundamentally, the argument raised with increasing vigor was that retrievability should in any case be feasible in order to preserve the ethical principle that future generations have retained freedom of choice to implement other actions (e. g., KASAM, 1988).

The specific technical issue of demonstrating that wastes can be retrieved has, thus, become a standard component of disposal planning, e.g., Svensk Karnbranslehantering (SKB), National Cooperative for the Disposal of Radioactive Waste (NAGRA), NIREX—as exemplified in the Swedish National Council for Nuclear Waste (KASAM) report cited above. For spent fuel disposal, as opposed to vitrified high-level wastes, there have been arguments for keeping the option of retrieving the fuel as a future energy source. The broader question of whether all steps in repository implementation, including site selection, are sufficiently reversible is more controversial.

For the technical community it is evident that the process of selecting candidate sites for investigation must recognize that any site selected may subsequently prove to be unsuitable. For the public, and especially among the local population at a candidate site, there can be an understandable apprehension that abandonment of a site will become increasingly difficult for the implementer as more resources are expended on investigations. At the two most intensively studied candidate sites in the world, Gorleben in Germany and Yucca Mountain in the United States, opponents claim that despite some negative findings relative to early expectations, investments are so high that the sites will never be voluntarily abandoned.

There are few examples of the site selection being voluntarily reversed by the implementer. This may, of course, be due to early screening steps in a selection program that result in only potentially suitable sites being selected as candidates. A case of potential site being subsequently judged technically unsuitable is an earlier site for New Mexico's Waste Isolation Pilot Plant cited in Sidebar F.1, Appendix F. There are, however, cases demonstrating that the siting decision can be reversed by the legal or regulatory system. The Sellafield public hearing in the United Kingdom and the abandonment in France of four sites before a law promulgated in 1991 and later of its first granite site provide illustrations. An illustration of a siting decision being reversed for societal rather than technical reasons is SKB in Sweden, which undertook to withdraw from selected potential siting areas if the local population were to express this wish in a consultative referendum. SKB did so in two cases, leading to an increase in public confidence in the Swedish siting process (Thegerström, 2000). Finland also voluntarily withdrew from a potential siting area at an early stage in its phased siting process.

The flexibility of the implementer to consider reversal of a siting step and the credibility of this option depends on alternative sites being available. This is a good argument for maintaining multiple siting options until there is sufficient consensus on the likely suitability of a single option to be chosen. The process in Finland is a positive example of this; up to, and even after, the selection of the site at Olkiluoto for a spent fuel repository, it was recognized that an alternative possibility at Loviisa remains. This contrasts with the situation in the United States and at Gorleben, where the perception became that there were no alternatives if the single option chosen were to prove unsuitable for any reason.

In addition to the reversibility and retrievability addressed above, the still broader Adaptive Staging attribute of flexibility is called for in this report. Flexibility means keeping options open and drawing lessons from earlier stages to improve later choices. How flexible are national waste management programs worldwide?

There has been an increase in the flexibility defining the goals for managing high-level waste and spent fuel. Twenty years ago, the universally accepted end point was a closed and sealed deep repository requiring no further monitoring or control to maintain safety. Recently, original discussions of alternatives have been revived (IAEA, 1997). Some programs are looking at very long-term (indefinite) storage (e.g., France, United States, Canada, and the Netherlands), some at the potential of transmutation (e.g., United States, Sweden, and Japan), and some are re-examining exotic options such as space disposal (United Kingdom) that were first examined 30 years ago (BNWL, 1974). There are also countries, such as Japan and Switzerland, that have embedded their preference for geologic disposal into their most recent legislation.

At a more practical level, flexibility is an attribute directly related to the repository design. There are excellent examples of programs that have kept options open. The Swedish PASS project (SKB, 1992) examined a range of disposal techniques and layouts, including deep boreholes, hydraulic cage designs and mined repositories. In Finland alternatives were also studied (Autio et al., 1996). The follow-up Swedish project, called JADE, looked at variants of emplacement techniques in more detail (Sandstedt et al., 2001). Japanese and Swiss studies, although based on well-defined reference disposal concepts, also looked at alternative designs and alternative host rocks. In the Waste Isolation Pilot Plant program, alternative buffer materials have been proposed.

Procedures with flexibility to allow learning experiences to influence later stages in implementation have also been defined in some national programs. A practical example that has already been implemented is the WIPP facility, where the allowable inventory of waste types for disposal has been progressively expanded as experience is gained. In Sweden, a demonstration disposal facility for an initial part of the inventory was proposed. In Switzerland, the advisory group EKRA recommended early emplacement of some wastes in a highly monitored system in order to observe the behavior over decades (EKRA, 2000), a concept in agreement with much earlier proposals of NAGRA (1985). In France, the program foresees an extended phase of underground experimentation in rock laboratories at potential sites.

The time scales proposed in staged waste disposal programs must be sufficient to allow the earlier learning experience to feed into later stages. The tendency of all program schedules to underestimate the time needed to move through a staged program is evident from an examination of the slippage in virtually all national programs. Recently, more realism in timing has been apparent. Even so, the French 15-year period allocated for exploring options in their 1991 law is proving too short. Even if sufficient knowledge may be expected by 2006 on the feasibility of a reversible repository in clay in the Bure area, insufficient progress will be made for a second laboratory, the site of which is yet to be determined. The Swedish program allowed more time for completion of its siting phase. Even in the strictly scientific and engineering areas there has been increasing awareness of the lengthy periods needed in staged waste disposal. For example, Finland's geologic program, one of the most advanced, acknowledges that underground exploration and repository development are phases that each last a decade or more. In general, most delays in planned schedules have resulted from underestimates of the societal challenges in the siting process.

In summary, the attribute of flexibility, including possible reversal, has been a feature of national disposal programs to varying degrees. The most contentious issues have not been over the degree of flexibility possible but the willingness of implementers to voluntarily reverse large steps (e.g., siting) and extending the time scales for completing stages and gaining experience for further work.

D.1.4 Auditability, transparency, and integrity

It is perhaps with regard to societal attributes that national waste management programs worldwide have been most criticized. The nuclear industry was born with a tradition of secrecy, and there was an unfortunate tendency for this to spill over into waste management programs. In the most controversial area, repository siting, examples are easily found. Even today, there is no open record of how the Gorleben site was selected in Germany in 1979 (IEG, 2001). In the United Kingdom, NIREX does not name the other sites that were considered along with Sellafield and Dounreay in its multi-attribute site-selection process (Dodgson et al., 2001). More positive examples are found in Sweden, Finland, the United States, and Switzerland, all of which have documented the sites considered throughout the progression of their programs.

Documenting the names of potential sites and the decision processes leading to narrowing the sites selection is less common. The United States published an extensive peer-reviewed, multi-attribute, analysis leading to the selection of three potential sites (DOE, 1986). The subsequent narrowing to a single candidate was, however, a policy decision made by the Congress and is obviously different from the decision mechanisms advocated in Adaptive Staging. The U.K. multi-attribute analysis refers to the sites only by number. In Switzerland, a more qualitative procedure was used and openly published to select one low/intermediate-level waste site from four candidates. Even so, recent independent auditing of the Swiss final choice of Wellenberg has produced criticism for a lack of transparency (KFW, 2002; NAGRA, 2001; Lambert, 1995).

At a deeper level, there is a question of transparency and auditability in the technical data produced and published by waste disposal organizations. Here the industry has a relatively good record. Many waste management organizations produce extensive report series documenting all their work. Technical audits are carried out within programs by experts and across programs by international groups often organized by the International Atomic Energy Agency and the Nuclear Energy Agency. There have been criticisms of the availability of data, but a more common complaint of critics or opponents is that international groups lack the resources and expertise to evaluate the large amounts of data produced in disposal programs.

Many national programs have largely independent review bodies that enhance auditability. In the United States these include: the Nuclear Waste Technical Review Board, the Advisory Committee on Nuclear Waste, and the Board on Radioactive Waste Management; in Sweden, KASAM; in France, the CNE; in the United Kingdom, the radioactive waste management advisory committee; in Switzerland, the KNE and the Wellenberg Group; in Japan, the nuclear waste advisory board (NSC), and in Finland, the advisory committee of the regulator (STUK).

A more common criticism of transparency in disposal organizations concerns not the availability of data but the access to the decision processes. In almost all countries, environmental groups believe that they have too little input to the decision process. Even within the general public, decisions all too often are seen as "decide, announce, defend" (DAD). Consulting the public before important decisions are made remains an exception rather than a rule. The U.K. siting process leading to the public enquiry where an open debate was held is a clear example of this. Although NIREX did start a consultation process and put considerable effort into it (NIREX, 1987), the initiative came too late, and in any case, political decisions led to the final choices. The negative outcome for the U.K. government has had such a strong impact that the program has been set back decades and the government's approach has radically changed to the extreme of consulting the public about how best the public should be consulted (DEFRA, 2001).

There are countries in which direct integration of the public into the process of repository development is guaranteed. This is sometimes through voluntary participation in siting processes (e.g., France, Sweden, Finland, and Japan), sometimes through public referenda (e.g., Switzerland and Sweden), and very often through organization of opportunities for public dialogue either with implementers or in the regulatory process (a good example being the USNRC rule-making process). The necessity for disposal organizations to focus on these societal issues, as well as the technical aspects of disposal is now documented and well recognized (NRC, 2001).

D.1.5 Responsiveness

Responsiveness refers to the need for stages to be sufficiently long to allow new knowledge to be gained for further decision-making but sufficiently short to ensure regular, open decision-making. At a technical level, there are examples of time scales being too tight to allow proper responses to experience gained. In the Swiss exploration program, the deep boreholes drilled at different sites followed one another so closely in time that valuable opportunities for learning and optimization were minimized. As mentioned above, the 15-year period set in France is too short to allow feedback from a second set of underground rock laboratory experiments. Because repository implementation and disposal operations at a deep repository will run for decades, there are opportunities for learning. A sufficiently long pilot phase can be useful and has been planned in some programs. If excavation of disposal space is not done all at once, but in parallel with the multiyear emplacement program (as proposed in Switzerland and the United States), efforts toward optimization can continue throughout the operational phase.

D.2 Successes and setbacks in non-U.S. national repository programs

There is a growing international consensus that repository programs have a higher chance of success when they proceed in a staged manner (NEA, 2002a, 1999; EDRAM, 2002). The staging approaches described by NEA and EDRAM have commonalties with Adaptive Staging. This awareness of the potential advantages of staging has arisen in large part because of the setbacks that various national programs have suffered when trying to proceed without sufficient intermediate checkpoints (i.e., a staged approach was more Linear than Adaptive).

In this section, the committee first gives prominent examples of blockages in disposal programs and, second tries to identify which attributes of Adaptive Staging may have led to more success. This exercise is, of course, made much easier with the benefit of hindsight; in all cases mentioned, the situation was much more complex than indicated here, and other causes for problems encountered can also be identified.

D.2.1 Programs that have experienced setbacks

In recent years, the most conspicuous, extensive, and expensive setbacks in disposal programs outside the United States have been in the United Kingdom, Germany, Canada, France, and Switzerland. These countries are especially noteworthy because in each case an active program enthusiastically promoted by the implementer was shortened by events that may have been less damaging if some or all of the attributes of Adaptive Staging had been applied. In all of these cases, many factors contributed to the course of events, a number of them political. It cannot be proven that the use of Adaptive Staging or any other approach would have made a difference. In some cases, decision makers put off difficult decisions because the potential benefits were local and not felt at levels (e.g., state, department, county, or canton) where the populations and political powers reside. In other cases, opposition to disposal projects was so entrenched that any approach was sure to encounter problems.

Disposal programs in countries not mentioned above have suffered setbacks that are less visible because the programs themselves were less active. A good recent overview of developments in many national programs is provided in Witherspoon and Bodvarsson (2001). Spain, for example, simply postponed for a decade all activities in its search for potential host sites when opposition became apparent (Astudillo, 2001). The Netherlands postponed all such work indefinitely; a 100-year interim storage facility was built, and the feasibility of extending this to 300 years is being investigated (Hageman and van de Vate, 2001). In Argentina, the cancellation in the early 1990s of the feasibility studies in high-level waste disposal and the abandonment of fieldwork were acknowledged as resulting from failure to integrate technical and societal aspects (Ninci et al., 2001). A brief example of the more dramatic failures in major programs in the United Kingdom, Germany, France, and Switzerland is presented below.

The United Kingdom applied for permission to construct an underground rock characterization facility at the Sellafield site, which was selected by the implementer (NIREX) after a multi-attribute utility analysis showed it to be the most suitable candidate (Dodgson et al., 2001). Following a long investigative process through a public inquiry, the inspector judging the application ruled that the preparations did not adequately satisfy environmental planning requirements and that there were insufficient data to justify the site selection. Although NIREX proposed a staged process with an underground laboratory preceding repository implementation, in practice, NIREX contradicted some important principles of Adaptive Staging.

For a long time there was little transparency in NIREX's work. The site-selection process was done in private without the names of most alternative sites made public. NIREX was not prepared for an in-depth discussion of the impacts that a repository might have on the region, arguing that this was a debate that should be postponed until suitability was demonstrated. The local population did not agree. The nuclear regulatory authorities were excluded from consultation because the process was formally only for non-nuclear planning permission.

By the time of the public enquiry, NIREX had vastly improved its transparency and its public consultation processes, but regaining public trust continued to be a difficult and slow task. The result of the Sellafield enquiry was that the substantial funds that had been invested were lost and the national waste management program was set back for years, perhaps decades. The government reacted by proposing such an extensive public consultation that no decisions to advance the project are expected within the next five years (DEFRA, 2001)

In Germany, the controversy around the Gorleben salt dome, selected as the only candidate host site in the 1970s, has led to a loss of money investment of the same magnitude as that lost in the United Kingdom. The debate over Gorleben is part of a larger technical and highly political national discussion involving two other issues: (1) how to proceed with the planned Konrad deep repository for non-heat-generating wastes and (2) how to proceed with the existing Morsleben salt repository in the former East Germany.

Gorleben was selected behind closed doors in Lower Saxony; even today no documentation on the justification for this decision is publicly available (IEG, 2001). Extensive exploration of the salt dome and its geologic setting showed that although no fatal flaws were identified in the site, it was less suitable than originally assumed. Objections to sites, however, are more often based on the selection approach than on assessment of their isolation potential. Much of the decades-long struggle between opponents and proponents has been caused by a lack of constructive interactions among the implementer and various stakeholders.

With respect to Adaptive Staging, recent objections focus on the remaining technical uncertainties and on assertions that the salt option offers too little possibility for retrieval. As a reaction to the dispute on the suitability of Gorleben, the German government imposed a moratorium on work at the site and set up a group, the *Arbeitskreis Auswahlverfahren für Endlagerstandorte* (AkEnd), charged with developing new siting criteria and a new approach to interacting with the German public on the siting issue. The proposals of AkEnd are closely allied with many of the principles of Adaptive Staging, with great emphasis being put on learning from advances in the technical area and in the social sciences. At the end of 2002, AkEnd will have completed its 3-year task of proposing a procedure for siting a safe geologic repository in Germany, taking into account technical and societal challenges (AkEnd, 2002).

In Canada, the financial repercussions of the major setback suffered in the national program in 1998 were less severe than those experienced in the United Kingdom and Germany (AkEnd, 2002). Financial commitments were lower in Canada, because no detailed site characterization had begun. The changes in approach to waste management, however, were even more fundamental. After a 16-year generic technical program, considered by many to be one of the most effective in the world, an extensive review took place to decide whether to move on to the siting phase.

The review panel, which included a minority of scientists, decided that although the technical basis for safety was good, there was insufficient public confidence in the safety (FEARO, 1998). The result was that the entire waste management program stopped, and the basic desirability of geologic disposal was called into question (Brown, 2000). Again, failure to integrate a wide range of stakeholder input into the process until too late was a key cause of the failure. The option of geologic disposal in deep crystalline rock was put to the public as the only alternative and was perceived by many to be chosen by an elite group of scientists and decision-makers.

In France and Switzerland the setbacks in the national programs have been serious but less fundamental, because they have not led to a total restructuring of programs or organizations. The French disposal implementer, the *Agence Nationale pour la gestion des Déchets Radioactifs* (ANDRA), was charged with identifying from available geologic data new potential sites in crystalline rocks after a government review panel disapproved of the original choice in the Vienne department (CNE, 1998). When a government-appointed mission suggested new potential sites, local representatives refused contact or even repelled envoys with violence (Merceron, 2000). This contrasts greatly with ANDRA's success in the potential siting area at Bure, where a shaft for an underground laboratory is under construction (Lebon et al., 2001). Bure, however, was a volunteer site with promising geology, and ANDRA also had good relationships with stakeholders.

The Swiss case provides a better example of setbacks that might have been avoided if the principles of Adaptive Staging had been applied. The Swiss disposal organizations, NAGRA and the *Genossenschaft für nukleare Entsorgung Wellenberg* (GNW), proposed the site of Wellenberg for a geologic repository in marl (a carbonate-rich clay) for low- and intermediate-level wastes. An application was submitted to start underground exploration that would lead to repository implementation, providing that expectations were confirmed. This application was turned down in a public referendum in 1995. The prime reasons, identified in later public polling (Kowalski and Fritschi, 2000), were that

- more permitting stages should be proposed (the initial application should be for exploration only, followed by a further application stage if a repository were to be proposed);
- more direct monitoring was desirable and waste should be more retrievable; and
- criteria that exploration results must satisfy should be provided fully transparently.

Since the public referendum in 1995, repository concepts have been adapted to satisfy the above requirements, in addition to recommendations of a special independent committee, EKRA, set up by the government (Wildi et al., 2000). The EKRA report focuses on stepwise procedures that make use of pilot, test, and demonstration facilities to gain knowledge and increase confidence in system behavior.

In 2002, another referendum was held on a revised project in which enhanced control and retrievability were offered, only an exploratory tunnel permit was sought, specific exclusion criteria during exploration were proposed, and much wider public involvment was initiated. The results (57 percent against) were more negative than the 1995 results (52 percent against). This demonstrates how difficult it is to regain sufficient support after a loss. It also provides a sobering lesson that all approaches to repository implementation in a democratic system face major challenges. The proposed host community was the only one in the canton that voted in favor, illustrating the common "doughnut" effect in which even if a local host community is prepared to accept the burdens of a wider public, communities close enough to feel affected but too far to derive direct benefits may still object to a repository.

D.2.2 Non-U.S. programs that have experienced greater success

The most successful spent fuel management programs today are acknowledged to be those in Finland and Sweden (NEA, 2002b). In each country, complete programs have been developed (Vira, 2001; Lundqvist, 2001), involving lengthy interim storage, followed by encapsulation of waste in copper containers and disposal in crystalline bedrock surrounded by a bentonite backfill. More impressively, the interim storage facilities are operational, and underground investigations at potential disposal sites have been identified and agreed to by the local communities. In Finland even the national government has agreed to the chosen site at Olkıluoto. On the other hand Sweden's "success" is qualified by two of the communities near the proposed sites vetoing the choice.

In the context of this report, it is noteworthy that both of these successful programs followed a staged site-selection process, both used underground rock laboratories as places for learning, and both placed great emphasis on continued direct contacts among personnel of the implementers, regulatory staff, and the public. Sweden, in particular, has been a leader in technology development with open access to its scientific work.

In Switzerland, notwithstanding the recent setback in the Wellenberg low-level waste project, significant successes have been achieved in the high-level waste program, in part by following some key principles of Adaptive Staging. The high-level waste disposal program was recognized to be transparent by regional, area, and local stakeholders. The siting process led to geologic investigations in a community that volunteered to offer a site for exploratory drilling (NAGRA, 2001). This process should lead to a major siting feasibility project. High-quality science, transparency, and encouragement of regular communications with all stakeholders have been continuously emphasized in the Swedish, Finnish, and Swiss programs.

An important caveat must be added before closing this brief account of program successes. Each of the examples given occurred in countries that have significantly different political systems, national cultures, and populations sufficiently small that maintaining contacts between implementers and stakeholders is a much simpler task. For instance, Sweden and Finland have incorporated in their programs, including the siting phase, many of the attributes of Adaptive Staging. It could still be, however, that the main reasons for success are simply cultural and political. These countries do not have a powerful state government to oppose national decisions. Where the implementers can deal directly with locals, they can often reach consensus. Although Adaptive Staging is a helpful approach, it is recognized that there are broader, largely political factors that must be taken into account.

In summary, meeting the criteria for Adaptive Staging does not guarantee success, but the committee believes that Adaptive Staging is a promising management approach because its attributes address many of the challenges facing high-level waste geologic repository programs, as discussed in Chapter 4 of this report.

References

AkEnd (Arbeitskreis Auswahlverfahren für Endlagerstandorte). 2002. DRAFT-Recommendations of the AkEnd. Committee on a Selection Procedure for Repository Sites. Safety Criteria and Site Selection Procedure for deep disposal of radioactive wastes. G. Arens. June. Federal Office for Radiation Protection.
Available at: http://www.akend.de/englisch/berichte/index_1024.htm

Astudillo, J. 2001. Geological Disposal of High-Level Radioactive Wastes in Spain. Pp. 247–258 in Witherspoon and Bodvarsson (2001).

Autio A., T. Saanio , P. Tolppanen, H. Raik, T. Vieno, and J.P. Salo. 1996. Assessment of Alternative Disposal Concepts. Posiva Technical Report 96-12, Posiva, Helsinki, Finland.

BNWL (Battelle Northwest Laboratory). 1974. High-Level Radioactive Waste Management Alternatives. BNWL-1900. Richland, Wash.: Pacific Northwest Laboratories.

Brown P. A. 2000: The Canadian Experience with Public Interveners on the Long-term in NEA (2002).

CNE (Commission Nationale d'Evaluation). 1998. Réflexions sur la Réversibilité des Stockages. Report. June. Paris, France: CNE.

Dodgson, J., M. Spackman, A. Pearman, and L. Phillips 2001. Department for Transport, Local Government and the Regions Multi Criteria Analysis: A Manual. February. London, United Kindgom: Transport Local Government Regions.
Available at: www.dtlr.gov.uk/about/multicriteria.

DOE (U.S. Department of Energy). 1986. A multiattribute utility analysis of sites under consideration for characterization for geologic waste disposal: A decision-aiding methodology. Washington, D.C.

DEFRA (U.K. Department for Environment, Food and Rural Affairs). 2001. Managing Radioactive Waste Safely: Proposals for Developing a Policy for Managing Solid Radioactive Wastes in the UK, London, United Kindgom: DEFRA.

EDRAM (International Association for the Environmentally Safe Disposal of Radioactive Materials). 2002. The Management of Radioactive Waste; A Description of Ten Countries. R. Lidskog, and A. Andersson (eds). Research Center Man-Technology-Environment. Örebro, Sweden: Örebro University.

EKRA (Expert Group on Disposal Concepts for Radioactive Waste). 2000. Disposal Concepts for Radioactive Waste. Final report. Report on behalf of the Federal Department for the Environment, Transport, Energy and Communication. January 31. Federal Office of Energy. Bern, Switzerland.

Euratom (European Atomic Energy Community). 2000. Concerted Action on the Retrievability of Long-Lived Radioactive Waste in Deep Underground Repositories. Final report. EU Project series Nuclear Science and Technology. EUR 19145 Nieschmidt. Brussels, Belgium: Euratom

FEARO. 1998. Report of the Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel, Ottawa, Canada.

Hageman, B., and L. van de Vate, 2001. Retrievable Disposal of Radioactive Wastes in the Netherlands. Pp. 199–204 in Witherspoon and Bodvarsson (2001).

IAEA (International Atomic Energy Agency). 1994. Siting of Geological Disposal Facilities, Safety Series No. 111-G-4.1. Vienna, Austria: IAEA.

IAEA.1995. The Principles of Radioactive Waste Management. Safety Series No. 111-F, IAEA, Vienna, Austria: IAEA.

IAEA, 1997: Issues in Radioactive Waste Disposal; 2nd Report of the Working Group on Principles and Criteria for Radioactive Waste Disposal, Chapter 2. IAEA-TECDOC-909, IAEA, Vienna, Austria: IAEA.

IEG (International Expert Group Goreleben). 2001. Repository project Gorleben. Evaluation of the present situation, Report prepared at the request of Gesellschaft für Nuklear Service mbH (GNS). Essen, Germany: IEG.

KASAM (Swedish National Council for Nuclear Waste). 1988. Ethical aspects on nuclear waste—Some salient points discussed at a seminar on ethical action in the face of uncertainty in Stockholm, Sweden, September 1987; National Board for Spent Nuclear Fuel, SKN Report 29. April. Stockholm, Sweden: SKN.

KASAM. 2000. Retrievability of high-level waste and spent nuclear fuel, Proceedings of an International Seminar in Saltsjöbaden, Sweden, October 1999, IAEA-Tecdoc-1187, Vienna, Austria: IAEA.

KFW (Kantonale Fachgruppe Wellenberg). 2002. Bericht zur Standortwahl Wellenberg
Available at: http://www.nw.ch/regierung_verwaltung/regierungsrat/aktuell/ Standortberichtinternet012002.doc.pdf.

Kowalski, E., and M. Fritschi, 2000. Has Wellenberg shown the way, or is it merely postponing the inevitable? In IAEA (2001) Retrievability of high-level waste and spent nuclear fuel. IAEA TECDOC 1187, Vienna, Austria: IAEA.

Lambert, A. 1995. Sedimentary rocks: Defining the options. In Disposal Programme for High-Level Waste. Nagra. Wettingen, Switzerland. Nagra Bulletin 25:22–33.

Lebon, P., B. Mouroux, and G. Ouzounian. 2001 Status of research on geological disposal for high-level radioactive waste in France, in Witherspoon and Bodvarsson (2001).

Lundqvist, B., 2001. The Swedish Program for Spent Fuel management (2001). Pp. 259–268 in Witherspoon and Bodvarsson (2001).

Merceron, T. 2000. A new siting process in France for a URL in Granite: Lessons learnt from the recent Consultation Mission. Pp. 127–129 in NEA (2000).

NAGRA (National Cooperative for the Storage of Radioactive Waste). 1985. Project Gewähr 1985. Nuclear Waste Management in Switzerland: Feasibility Studies and Safety Analyses. NGB 85-09. Wettingen, Switzerland: NAGRA.

NAGRA. 2001. Sondierbohrung Benken, Untersuchungsbericht [Benken borehole, investigations report, in German]. Nagra Technical Report NTB 00-01. Wettingen, Switzerland: NAGRA.

NEA (Nuclear Energy Agency). 1995. The Management of Long-lived Radioactive Waste. The Environmental and Ethical Basis of Geological Disposal. An International Collective Opinion. Paris, France: Organization for Economic Cooperation and Development.

NEA. 1999. Confidence in the Long-Term Safety of Deep Geological Repositories. Its Development and Communication. NEA 01809. Paris, France: Organization for Economic Cooperation and Development. Available at: http://www.nea.fr/html/rwm/reports/1999/confidence.pdf.

NEA. 2002a. Stepwise Decision Making In Radioactive Waste Management: Status, Research, Issues, NEA/RWM/FSC. Paris, France: Organization for Economic Cooperation and Development.

NEA. 2002b. Second Forum on Stakeholder Confidence. Stakeholder Involvement and Confidence in the Process of Decision Making for the Disposal of Spent Nuclear Fuel in Finland. Workshop Proceedings. Turku, Finland. November14-16. Paris, France: Organization for Economic Cooperation and Development.

Ninci, C., A. Bevilaqua, L. Jolivet, E. Maset, R. Ferreyra, A. Vullien, O. Elena, L. Lopez, A. Maloberti, H. Nievas, N. Reyes, and J. Zarco. 2001. Deep Geological Disposal Research in Argentina. Pages 15–22 in Witherspoon and Bodvarsson (2001).

NIREX (Nuclear Industry Radioactive Waste Executive). 1987. The Way Forward: A Discussion Document. The Development of a Repository for the Disposal of Low and Intermediate-Level Radioactive Waste. Harwell, United Kingdom: NIREX.

NRC (National Research Council). 2001. Disposition of High-Level Waste and Spent Nuclear Fuel. The Continuing Societal and Technical Challenges. Washington, D.C.: National Academy Press.

Sandstedt, H., K. Pers, L. Birgersson, L. Ageskog, and R. Munier, R. 2001. Project JADE. Comparison of Repository Systems. Executive Summary of Results, SKB Technical Report TR-01-17. Stockholm, Sweden: SKB.

SKB (Swedish Nuclear Fuel and Management Co.). 1992. Project on Alternative Systems Study (PASS). Final Report. SKB Technical Report TR 9304. Stockholm, Sweden: SKB.

Thegerström, C. 2000. Ten Years of Siting Studies and Public Dialogue: The Main Lessons learnt at SKB. In Stakeholder Confidence and Radioactive Waste Disposal. Workshop Proceedings. Paris, France: NEA.

Vira, J. 2001. Step-wise decision-making in trial: The case of Finland. Paper presented at the 9th International High-Level Radioactive Waste Management Conference. April 29–May 3. Las Vegas, Nev.

Wildi, W., D. Appel, M. Buser, F. Dermange, A. Eckhardt, P. Hufschmied, H.R. Keusen, and M. Aebersold. 2000. Disposal Concepts for Radioactive Waste, Final Report. Bern, Switzerland: Federal Office of Energy.

Witherspoon, P. A. and G. S. Bodvarsson. 2001. Geological Challenges in Radioactive Waste Isolation, Third Worldwide Review. LBNL-49767. Berkeley, Calif.: Berkeley Lab Press.

Appendix E

Environmental Monitoring and Adaptive Staging

Essential steps in an Adaptively Staged geologic repository program are: (1) monitoring the repository environment, including its component engineered barriers as well as its natural barriers; (2) scientific and programmatic evaluation of the new data, and (3) using this data in decisions to move the program forward or to modify operational strategies. Adaptive Staging cannot exist without adequate monitoring.

Figure E.1 shows the types of monitoring activities during various phases of a repository program. An early and ongoing monitoring program is one of the essential elements of Adaptive Staging. During early preoperational stages monitoring is essential to characterize the site and to provide background (or baseline) levels for key parameters. As the repository stages evolve over time, monitoring emphasis and priorities shift to near-field and *in situ* monitoring while far-field, surface, and borehole monitoring activities continue. During closure, monitoring measurements must provide assurance of the effectiveness of seals and the security of the waste. After closure, *in situ* monitoring may become infeasible, and more reliance will have to be given to indirect geophysical and remote-sensing methods.

Monitoring the repository environment will be most feasible and most valuable for Adaptive Staging during the operational phase, after requisite baseline measurements have been acquired. If the operational phase were to begin with a preliminary pilot-scale activity, intensive *in situ* monitoring of the pilot disposal rooms, their environments, and their engineered barriers would be essential for learning and scaling up to a fully operational activity. A pilot disposal operation would also serve as a testing ground for monitoring methodology.

An overview of monitoring needs and methods is presented in Table E.1. The lists in the last three columns relate to the environment in the first column, but there is no correlation implied between the order of the lists of columns 3 and 4 and the components listed in column 2. This table is not comprehensive and all inclusive; rather, it illustrates the complexity and varying needs of a monitoring program for a high-level radioactive waste repository. In addition, by the time repository monitoring for an operational phase actually occurs, these methodologies may well have advanced far from what is now available.

Monitoring to provide data for scientific input to decision-making may be either intrusive or noninvasive. Intrusive methods may offer the best approach to direct observation of engineered barriers, waste canisters, and surrounding near-field environments. However, intrusive methods pose a risk because the observation method itself might degrade the integrity of the repository. In addition, the measuring apparatus (e.g., drill hole or sensor) perturbs the local environment, often to an unknown extent.

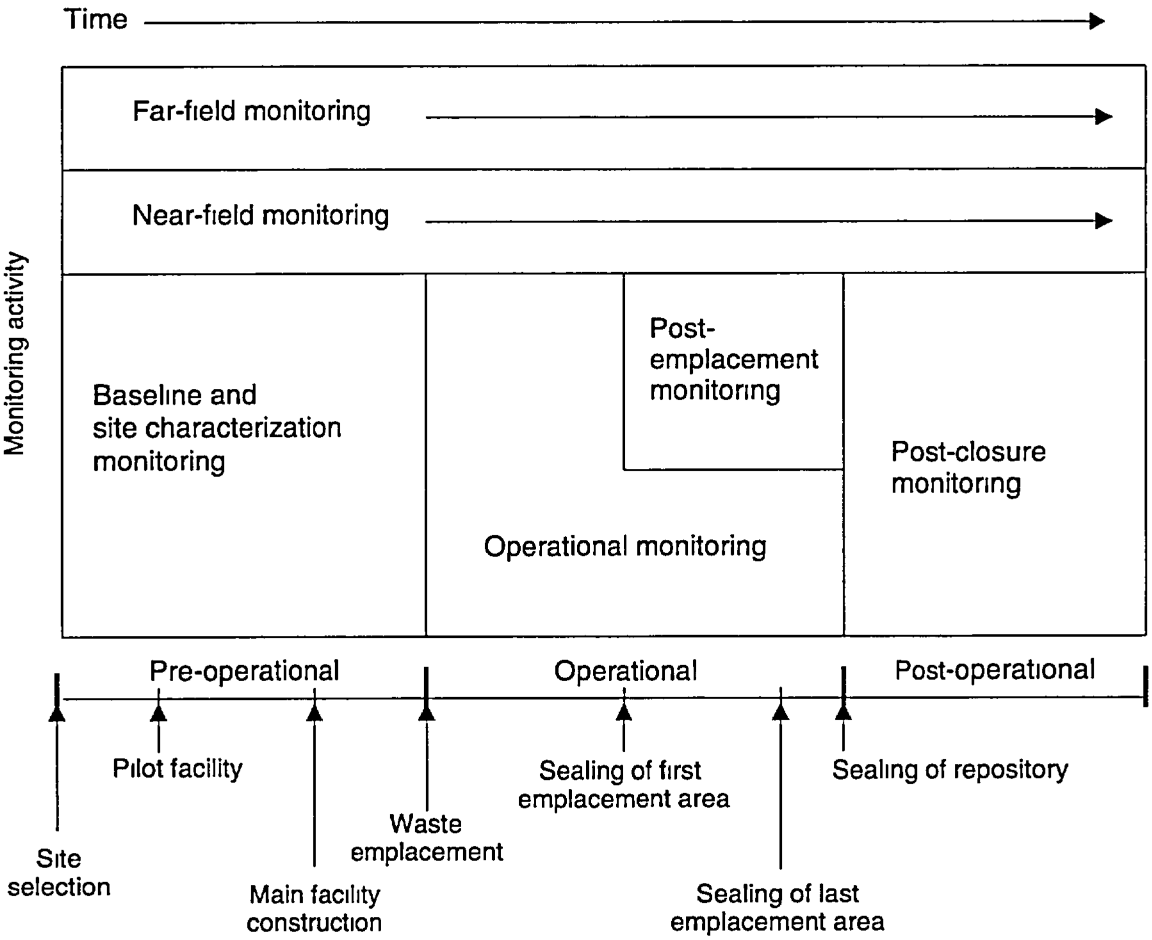

FIGURE E.1: Types of monitoring activities during various phases of a repository program.

Therefore, direct measurements of conditions within the repository and the near-field environment may be most feasible during the construction and operational phases of the repository, but would be impractical (with present technology) in the post-closure era (Figure E.1). One of the research priorities during the next few decades is to develop improved indirect methods to be used during the post-closure stage to monitor critical parameters within the repository.

Monitoring in a repository program can serve a variety of purposes (IAEA, 2001). These purposes may change as stages evolve. Pre-closure monitoring goals include: (1) providing baseline measurements of thermal, chemical, mechanical, geological, and biological conditions undisturbed by the repository system; (2) providing data for analyzing actual system (and component) performance and comparing the data with expectations, including model calculations (compliance); (3) providing data to be used at each stage in decision-making; (4) detecting any system behavior or failures that could harm the environment or human health (compliance); (5) safeguarding nuclear materials; (6) providing data that ensure responsibility and liability; (7) providing information for societal confidence in repository performance; (8) ensuring health of workers during the operational phase of the repository; and (9) assuring compliance with existing regulations.

TABLE E.1. Overview of Selected Monitoring Requirements for a Geologic Repository for High-level Radioactive Waste. This table is not meant to be all-inclusive.

Environment	Examples of Repository Components	Examples of Parameters and Processes	Examples of Methodologies
Repository	• Tunnels and Rooms (including coring walls, floors, and ceilings in host rock) • Atmosphere • Waste Packages/Containers • Buffer Materials • Backfill Materials • Seals • Other Engineered Barriers • Monitoring Components (e g., sensors and wiring)	• 3D Dimensional Change • Stress/Strain • Corrosion • Oxidation/Reduction • Temperature • Mineralogical Composition • Air and Gas Composition • Fluid Content and Composition • Structural Integrity • Vapor Saturation/Humidity • Organic Activity (microbial)	• Direct Sampling with wells or cores (both continuous and discontinuous) • Emplaced Meters and Sensors for Direct Nondestructive Measurement of Physical and Chemical Parameters • Data Transmission Hardware (electrical cables and wires, fiber optic cables, wireless transmission) • Remote Sensing and Surface Geophysics (including "time-lapse" sequencing) • Clinometers • Tomographic Methods (including Gamma-scanning techniques) • Acoustic methods
Natural (both near-field and far-field)	• Atmosphere • Land Surface • Surface Water (streams, lakes, wetlands, etc.) • Vadose Zone (unsaturated zone) • Saturated Zone • Host Rocks (near-field and far-field) • Deep Bedrock • Microbial Environment	• Precipitation (and selected other meteorological and climatic factors) • Temperature (air, water, rock) • Chemical Composition (air, water, rock) • Radionuclide Content (air, water, rock) • Fluid Pressure (hydraulic head) • Water Flux (surface water, vadose zone, saturated zone) • Erosion and Sediment Transport • State of Stress • Seismicity • Land Surface Deformation and Erosion • Biological activity	• Shallow & Deep Boreholes (variety of direct measurement options for hydraulic and compositional parameters and sample collection) • Weather Stations (variety of instrumentation) • Air Monitoring • Particulate Collection • Temperature Probes • Surface Water Monitoring Stations (flow, stage, quality) • Advanced GPS Surveys • Strain Meters • Seismometers • Borehole Geophysical Methods (including advanced tomographic methods) • Surface Geophysical Methods (including "time-lapse" sequencing) • Clinometers and Tilt Meters • Remote Sensing (aerial and satellite surveys)

Post-closure monitoring goals also include 2, 4, 5, 6, and 7 above. A widely accepted "principle" of the international community is that long-term safety of the repository must not rely on institutional controls (i.e., the capability to monitor the repository after it has been sealed and closed [IAEA, 2001]). However, monitoring after closure should be continued for as long as any institutional control and memory persists to provide input for maintaining confidence in the performance of the system.

The monitoring methodology must not threaten the safety or security of the site or in any way compromise the safety and integrity of the repository by providing a potential pathway for release of radionuclides to the environment or intrusion into the repository. If wiring, pipes, holes, or tunnels are required to transfer information from the sensors to the recorders and observers, then those pathways might represent weaknesses in the multiple barrier approach to safety and would be unwise. Consequently, monitoring of conditions within the repository itself, including performance of the engineered barriers and waste canisters, will ultimately have to rely on either indirect noninvasive methodologies (such as remote sensing and geophysical methods) or long-term sustained wireless transmission of information from *in situ* sensors (which will require additional research and development). One of the grand challenges in this regard is placement of monitoring stations. While maintaining a secure repository, stations must be spatially arranged to provide the greatest probability to detect a leak if one occurs. Even though a monitoring system for a waste repository must be able to detect even small releases of radioactivity from waste containers into the repository environment, the strategy should be planned to detect precursors of possible releases, including deterioration or failure of engineered barriers. Within the repository this could mean monitoring the physical and chemical integrity of the waste containers and looking for degradation products of canister and engineered barrier materials. On a regional scale (far-field environment), monitoring must detect any environmental changes that could affect the fate and transport of any potentially leaked radioactive materials, or that would significantly alter the assumptions made during site characterization and licensing.

Before construction and operation, in the pre-closure stage, a comprehensive monitoring plan over the entire site must be developed to acquire a database of environmental information that characterizes the conditions, properties, and behavior at the site before any disturbance of background conditions. Establishment of baseline conditions should be essentially completed during the site-characterization stage. Examples for a well-characterized site are given in Table E.1.

Baseline measurements provide the foundation for formulating conceptual models and accessing future system behavior and are required for making decisions related to system performance. Reliable observations must be attained by techniques of varying sophistication, evaluated and synthesized with related data, and archived so that the previously gained information is readily available for comparison with future system measurements. Information-gathering of this type requires long-term institutional commitment so that baseline data are available to future generations. A monitoring strategy that provides information on poorly understood aspects of the systems is imperative. Heterogeneities in both time and space are inherent in natural systems. A strategy of measurements must be made that incorporates this inherent variability into the baseline. Because of these temporal and spatial variations, baseline monitoring must be ongoing and repeated at appropriate frequencies so that future variations in response to waste emplacement can be distinguished from inherent background variability.

E.1 Remote monitoring

Geophysical and remote-sensing approaches are prominent in Table E.1's list of example methodologies, and those items listed represent broad categories that encompass many specific tools. Two significant advantages of many of these methods are that they are noninvasive and that their signals can represent properties of relatively large areas or volumes of material (as opposed to point values). Geophysical methods would also be of particular value for the purpose of safeguarding nuclear materials in that they can detect undeclared or unapproved tunneling activities and movement of waste containers. The potentially strong reliance on geophysical methods suggests that a range of techniques can be applied and repeated throughout the site characterization, construction, and operational phases of a repository to provide a basis of comparison with surveying results after site closure. For example, Clark and Kleinberg (2002) illustrate the use of time-lapse seismic surveying to show how petroleum reservoir properties change over time; such an approach can be extended to environmental monitoring of a repository. Future developments in remote sensing may also provide breakthrough technologies with direct application.

Geophysical and remote-sensing approaches provide examples of significant advances in monitoring technology during the past few decades. This rate of progress will continue and it is difficult today to conceive of what future advances will bring. One recent example that may have direct use in a repository program, especially where it is important to detect regional changes in the water-table configuration, is the use of satellite microgravity surveys (Wahr and Molenaar, 1998; Parker and Pool, 1998). Continued future advances in monitoring is a major reason why a repository monitoring program must be Adaptive and allow incorporation of new and better technologies and methodologies.

E.2 Monitoring flow and transport

Some components and constitutive properties listed in Table E.1, such as water, chemicals, and microbes, are subject to migration. It is this potential for transport of radionuclides from the repository that is the primary concern for long-term safety. Prediction and detection of transport (rates and pathways) depend on how accurately and precisely the fluid flow field is defined and how well the site-specific flow process are understood conceptually. Mapping of the flow field is a key element in the establishment of baseline conditions and requires adequate monitoring of regional hydrologic conditions. Such data are largely obtained through direct measurements of hydraulic head (or fluid pressure or potential) in boreholes, and tracer tests, coupled with ongoing interpretation of the hydrostratigraphy.

Monitoring and sampling in the saturated zone are relatively straightforward, both conceptually and technically. Understanding flow directions in a saturated zone entails defining the hydrostratigraphy and mapping the water table, potentiometric heads in deeper aquifers, and the three-dimensional distribution of equipotential surfaces. The definition and monitoring of the flow field is itself a staged operation, as the early data from initially drilled observation and test wells provide the basis locations of additional wells. A major monitoring problem at repository sites is the evaluation of the adequacy of the definition and understanding of the flow field relative to the need for additional monitoring wells. Because drilling is expensive, it is a difficult management decision to evaluate the tradeoffs between budgetary constraints and the desire for more precision. An Adaptive Staging approach is needed for such decisions. One basis for a decision might be the consideration of whether the level of understanding would make it likely that a potential release of radioactive contaminants from a repository failure would be detected by either a near-field or far-field monitoring network. For instance, at the Yucca Mountain site, the flow field is not yet adequately understood or defined with sufficient accuracy to have confidence in an early-warning monitoring network in the saturated zone.

Direct monitoring and sampling of the saturated zone use access through wells or boreholes. These are generally constructed with steel casing. Experience in the water well and petroleum industries indicates life expectancies for wells on the order of tens of years. This is very short relative to the expected life of a repository. Consideration should be given to the durability and longevity of typically constructed boreholes and materials and the need for improvement. One consequence of well collapse or other failure is the loss of continuity in the monitoring record, but a more serious outcome may be that a collapsed and abandoned well could provide a permeable pathway that acts as a short circuit for the release of contaminants to the accessible environment. That is, under certain circumstances abandoned or inaccessible monitoring wells may defeat the effectiveness of natural barriers.

In the unsaturated (or vadose) zone above the water table, fluid pressure is generally less than atmospheric, so water will not flow into an open borehole (or into repository drifts). Because water is under tension, the definition of fluid flux and monitoring in an unsaturated zone is much more complex and difficult to predict than for a saturated zone (e.g., NRC, 2001). The Yucca Mountain site is an exception to the general trend in site placement with respect to the water table for high-level repositories. That is, in this case the repository will be located in a thick unsaturated zone in an arid climatic zone. Here the unsaturated zone is heterogeneous and highly fractured. This and the low fluid flux through the unsaturated zone make the characterization and monitoring of infiltration and seepage extremely difficult.

Paradoxically, some of the characteristics that make characterization and monitoring difficult are the same characteristics that enhance the safety of the site. Because the unsaturated zone has high fracture permeability, air circulation can affect moisture movement and can also be a transport agent. Circulation of both air and water produces multiphase flow and transport processes, which are nonlinear and highly affected by temperature variations; this natural phenomenon would be greatly enhanced by emplacement of heat-generating wastes. Stephens (1995) includes a detailed discussion of the state of the art of monitoring the vadose zone and points out that "the field is rapidly evolving toward new and more sophisticated methods...." Aside from repository considerations, Yucca Mountain constitutes a field laboratory for innovative new methodologies for characterizing and monitoring unsaturated zone flow. However, for repositories that would be situated deep in the saturated zone, as are most proposed sites throughout the world, knowledge of the details of flux through the unsaturated zone are not critical to the evaluation of site safety.

E.3 Application of monitoring data

A long-term environmental monitoring program is also critical for assessing extreme, and rare, hydrological and geologic events. Such random events occur so infrequently that establishing a historical basis for predicting their risk to the repository is extremely difficult. For example, large, intense storms with accompanying precipitation or high-magnitude seismic events might occur at the site only once in 100 to 500 years. These "rare" events occur at frequencies outside a human lifespan and may not have yet been observed at the repository site. However, their impact is such that they may pose the greatest stress and danger to the repository during its regulatory lifetime (10,000 years).

Pre- and post-closure monitoring lies at the core of the early-warning strategy. Monitoring must be able to ascertain even minute changes in the thermal, chemical, mechanical, biological, hydrological, atmospheric, geological, and geophysical status of the entire repository environment that might reflect, or affect, the integrity of any aspect of the site. These changes may be recorded in the properties of the material or in the physical or biological processes that affect the site. A complicating factor is that processes are coupled such that the feedback among processes may have unknown effects on related processes. In addition, the relationship between the *in situ* processes and their external manifestations that allow for observation and detection may be uncertain. Detection limits may not be sufficiently low. Consequently, monitoring must be systematic and comprehensive both in spatial extent and temporal frequency.

E.4 Relationship between monitoring and other scientific programs

Adaptive Staging emphasizes learning; monitoring delivers some of the new information from which one can learn. The repository learning process should be linked firmly to the scientific analysis of data collected by the monitoring program; hence, monitoring should be firmly linked to a long-term science and technology program. Overall, the targets and design of the monitoring network must be based on the scientific and conceptual understanding (and conceptual uncertainty).

The performance confirmation program is a process to test and evaluate whether the repository system is working as expected and within the acceptable safety margin. The tests and evaluations (i.e. monitoring) must be based on observations of changes in natural and engineered systems and components. Within the context of Adaptive Staging, performance confirmation is an ongoing activity to maintain confidence in safety and to provide feedback to managers and engineers on the potential need for redesign of construction or operational details.

Monitoring provides one basis for performance confirmation, because it provides data representing direct and indirect observations of the natural and engineered systems that comprise the geologic repository. Scientific analysis of monitoring data provides the second basis for performance confirmation, as it is the process by which observed behavior will be compared with expected behavior and the significance of deviations evaluated. Therefore, with Adaptive Staging the monitoring program should be closely linked both to the performance confirmation program and to the long-term science and technology program.

Monitoring methodologies must be adapted during the long time spans of the repository to take advantage of advances in technology. Figure E.2 shows the committee's perspective on the interdependence and interaction among the long-term science and technology program, the performance confirmation program, and the monitoring program. The science program must interact with the performance confirmation program, but each has many independent goals and functions. On the other hand the monitoring program provides data to both of these programs and must receive direction and guidance from the other two programs while its products and output feed data for their respective analyses; the monitoring program would likely have few functions independent of the needs of the other two programs.

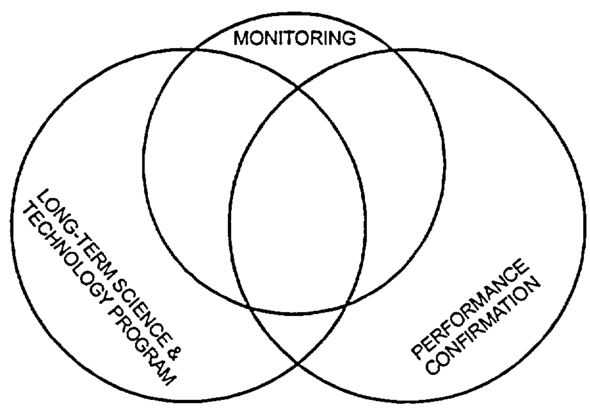

FIGURE E.2 Venn diagram showing conceptual relationship among the monitoring, long-term science and technology, and performance confirmation programs.

References

Clark, B., and R. Kleinberg. 2002. Physics in oil exploration. Physics Today 55 (4):48-53.

EPRI (Electric Power Research Institute), 2001, Performance Confirmation for the Candidate Yucca Mountain High-Level Nuclear Waste Repository, Final Report-December. Palo Alto, Calif.: EPRI.

IAEA (International Atomic Energy Agency). 2001. Monitoring of Geological Repositories for High-Level Radioactive Waste. TECDOC-1208. Vienna, Austria: IAEA.

NRC (National Research Council), 2001. Conceptual Models for Flow and Transport in the Fractured Vadose Zone. Washington, D.C.: National Academy Press.

Parker, J. T. C., and D. R. Pool. 1998. Use of microgravity to assess the effects of El Niño on ground-water storage in southern Arizona: U.S. Geological Survey Fact Sheet 060-98.

Stephens, D. B. 1995. Vadose Zone Hydrology: Boca Raton, Fla.: Lewis Publishers.

Wahr, J., and M. Molenaar. 1998. Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE: Journal of Geophysical Research 103(B12):30,205-30,229.

Appendix F

Overview of U.S. Geologic Repository Programs

The U.S. national commitment to achieve permanent isolation is the basis for the Nuclear Waste Policy Act (NWPA) of 1982 and its 1987 amendment, the Energy Policy Act of 1992, and regulations such as *Public Health and Environmental Protection Standards for Yucca Mountain, Nevada* (Title 40 of the Code of Federal Regulations Part 197) and *Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain* (10 CFR 63). The NWPA has identified the Department of Energy (DOE) as the implementer of the repository program and the Nuclear Regulatory Commission (USNRC) as the regulator.[1] The Congress also instituted the Nuclear Waste Technical Review Board (NWTRB) to "evaluate the technical and scientific validity of activities undertaken by the Secretary [DOE]." in the Yucca Mountain project. The NWTRB reports its findings, conclusions, and recommendations not fewer than two times per year to the Congress and to DOE and the Advisory Committee on Nuclear Waste, advises the USNRC on a wide range of waste-related matters, including Yucca Mountain.

DOE is also the implementer of another geologic repository for radioactive waste: the Waste Isolation Pilot Plant (WIPP). This geologic repository, located in southeastern New Mexico, is currently accepting transuranic[2] waste and is regulated by the U.S. Environmental Protection Agency and the State of New Mexico (see Sidebar F.1).

F.1 The Yucca Mountain project

Congress established the regulatory framework for siting, characterizing, constructing, operating, and closing a permanent geologic repository. DOE planned its baseline roadmap and milestones for the high-level waste repository on the basis of the U.S. regulatory framework. This schedule is referred to as the "reference schedule" and is briefly described below. The schedule is further detailed in the Yucca Mountain's Total System Description report (DOE-OCRWM, 2001b).

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[1]The USNRC enforces the environmental standards for disposal of high-level waste in a geologic repository promulgated by the U.S. Environmental Protection Agency in 40 CFR 197. Based on these standards, the USNRC published its disposal regulations in 10 CFR 63.

[2]Transuranic waste consists primarily of clothing, tools, equipment, and debris contaminated with alpha-emitting nuclides with a half-life greater than 20 years and heavier than uranium. Transuranic waste was created from the manufacture of nuclear weapons and is still being generated during the cleanup of weapon production sites.

Sidebar F.1 The Waste Isolation Pilot Plant

Located in southeastern New Mexico, the Waste Isolation Pilot Plant (WIPP) is a geologic repository for disposition of U.S. defense-generated transuranic waste. The waste emplacement area is excavated in a bedded salt formation 660 meters below the surface (NRC, 2001a).

WIPP is the world's first licensed deep subsurface geologic repository for radioactive waste, and it is the result of almost four decades of scientific and technical work (NRC, 1996). The site was selected in 1975, and in 1992, through the Land Withdrawal Act, DOE became the owner of the land on which the WIPP facility was to be constructed. In 1996, DOE submitted a certification application to the U.S. EPA to open the repository. Certification was granted in 1998 (DOE-CAO, 1996). The State of New Mexico regulates the hazardous waste component of transuranic waste and monitors operations at the facility. New Mexico granted a hazardous-waste-handling permit to WIPP in 1999. WIPP has been in operation since March 1999.

The WIPP Program Has Attributes of Both Adaptive Staging and Linear Staging

The WIPP program has some elements of Linear Staging. The program's schedule was rigid and did not take into account delays caused by public resistance or unexpected technical findings. The program adapted to different circumstances but often only as a last resort to external critiques. The program was not designed to take maximum advantage of systematic learning but responded after the fact to unanticipated results. For example, there was no *in situ* pilot stage with radioactive waste after the site was certified by the U.S. Environmental Protection Agency and permitted by the State of New Mexico. Learning occurred but only when triggered by external factors or by operational experience. Once waste was emplaced underground, only limited monitoring and tests were performed.

The WIPP program also has some attributes of Adaptive Staging.

- *Reversibility.* An example of reversibility in the WIPP program was that DOE abandoned a potential site for the facility in New Mexico because of information gathered during site characterization in 1975.
- *Transparency.* The WIPP project has been subjected to independent external scientific and technical reviews throughout its history. Beginning in 1979, Congress provided funding to New Mexico's Environmental Evaluation Group to oversee WIPP. The director of this group is appointed by the State of New Mexico. Since 1978, the National Academy of Sciences has continued to provide scientific and technical advice. These technical oversight groups have increased WIPP's credibility and triggered many program adaptations. The compliance certification process was carried out transparently, according to rules agreed on, in advance, by all participants.
- *Responsiveness.* The program was responsive to concerns from parties external to the program. For instance, political resistance changed the scope of the facility: at one point early in WIPP's history, DOE

planned to use it as a research-and-development facility for demonstrating the safe disposal of transuranic waste and commercial spent nuclear fuel. In 1980, the Congress restricted WIPP's scope to disposing of transuranic waste. Later this restriction was reinforced when the WIPP Land Withdrawal Act of 1992 banned the shipment of high-level waste or spent nuclear fuel to WIPP.

The scientific program was responsive to the technical oversight groups and peer panels, frequently modifying and implementing new studies based on their suggestions and recommendations. The engineered barrier system was modified in response to technical concerns identified during the performance assessment studies (e.g., backfilling materials were introduced). In addition, a new type of backfill, magnesium oxide, was introduced to the program to provide an additional safety factor prior to the certification application. The emplacement of magnesium oxide was later modified in response to lessons learned from operational experience and improved chemical modeling. The repository horizon also changed in response to information acquired during excavation of the first panel of disposal rooms.

Compared to the original baseline roadmap, the program experienced significant delays and cost overruns. Waste emplacement began 10 years later than the original schedule, when the Environmental Protection Agency was designated the regulator and additional compliance studies were initiated. In spite of these delays and costs overruns, WIPP is considered a successful geologic repository program because it is now in operation. The success of WIPP can be attributed to the following factors (University of New Mexico, 2001):

- There was (and continues to be) public support for WIPP in communities immediately near the repository and, albeit not as strong, in New Mexico. The public was relatively supportive of the WIPP for three reasons. First, WIPP provides jobs and economic development opportunities. DOE and the local community both benefited from working cooperatively. Second, there is a long history of involvement of New Mexico in national defense activities—Sandia National Laboratories and Los Alamos National Laboratory are two of New Mexico's largest employers—and WIPP is viewed by many citizens as a legitimate national defense activity because it provides a solution to the defense transuranic waste problem. And a third related issue, the public did not perceive their state as being the "nation's radioactive waste dump" because no commercial waste is to be sent to WIPP.
- WIPP is located in a sparsely populated, semiarid region with little potable groundwater, and the bedded salt is expected to provide an effective long-term barrier to the migration of transuranic radionuclides. Moreover, the U.S. Environmental Protection Agency requires a recertification of WIPP every 5 years, and the state of New Mexico has authority to suspend or revoke WIPP's hazardous waste facility permit.
- The public perceives transuranic waste as less risky than high-level waste. Defense transuranic waste has a relatively low radionuclide content and produces relatively little heat. Consequently, there is expected to be little thermal energy generated in the repository to promote processes

that could complicate predictions of containment.

Although some of these factors are site or waste specific, there are lessons from the WIPP program that can be applied to high-level waste repository programs—most notably, allowing sufficient time to undertake the scientific and technical investigations necessary to demonstrate site suitability; reversing course if there are questions about safety; obtaining external, independent scientific and technical reviews of these investigations; and seeking and demonstrating responsiveness to external input.

Science and engineering details for the repository are published in the *Yucca Mountain Science and Engineering Report* (DOE-OCRWM, 2002a). The starting point for this committee's work was the DOE's 2001 schedule (DOE-OCRWM, 2001b), but this has already undergone major changes (e.g., license application is now delayed from 2002 to December 2004).

F.1.1 Selection of a geologic disposal option (1982)

Building on early recommendations by the National Academy of Sciences (NRC, 1957), the NWPA designated geologic isolation as the choice for disposal of high-level waste and commercial spent nuclear fuel (NWPA, 1982). Although geologic disposal has often been questioned by groups that favor long-term, monitored surface storage, the original choice was openly documented (NRC, 2001b). This choice caused little or no controversy or opposition before the contentious issue of actually siting a facility occurred.

The NWPA requires the USNRC to limit DOE to disposal of no more than 70,000 metric tons of heavy metal (MTHM) of high-level waste (currently estimated to be composed of 63,000 MTHM of commercial spent fuel and 7,000 of defense-related waste) in the first geologic repository "until such time as a second repository is in operation" (NWPA, 1982; Section 114[d]). There are currently no plans for a second high-level waste repository. The NWPA Amendments of 1987 require DOE to report back to Congress between 2007 and 2010 on the need for a second repository (NWPA, 1982; section 161b).

F.1.2 Site selection and characterization (1982-2002)

The NWPA of 1982 directed DOE to select sites across the United States for characterization as candidate repositories for high-level waste. It also directed DOE to submit to the Congress a recommendation for a second site from any sites already characterized as a potential second repository. In the mid-1980s DOE conducted a program of site screening and selection, resulting in first nine, then five, and finally three sites selected for characterization. Seventeen states were initially screened for the second repository location. DOE ultimately recommended three locations as candidates for site characterization for the first repository: (1) Yucca Mountain, Nevada; (2) Hanford, Washington; and (3) Deaf Smith County, Texas. The siting process developed in stages, initially narrowing the number of candidate sites by multi-attribute utility analyses, which was reviewed by the National Research Council.

In a 1987 amendment to the NWPA the Congress directed DOE to concentrate only on characterization of Yucca Mountain[3] and to terminate activities at the other candidate sites for the first repository, and to "indefinitely postpone" siting activities associated with the second repository. DOE then built an *in situ* exploratory study facility within the potential repository horizon for site characterization at Yucca Mountain. The siting phase officially ended on July 9, 2002, when Congress determined that the suitability of Yucca Mountain allowed for further development and authorized DOE to submit a license application. As allowed by law, the governor of Nevada filed a "notice of disapproval," that was subsequently overridden by votes in Congress. The next step in DOE's repository program is to obtain a USNRC license for construction authorization. The application for construction authorization must contain a proposed design for the repository.

The total design capacity is assumed to be approximately 70,000 MTHM of commercial spent nuclear fuel, including mixed-oxide (MOX) fuel; 2,500 MTHM of defense-related spent nuclear fuel, including naval waste; and approximately 22,000 canisters of vitrified high-level waste, including some canisters containing immobilized plutonium waste form contained in high-level waste glass (DOE-OCRWM, 2001a). In addition to high-level waste and spent nuclear fuel, Yucca Mountain is anticipated to receive other wastes as noted in Sidebar F.2.

As part of site characterization and license application DOE is currently studying the natural system (e.g., geology, hydrology, and climatology) and the engineered barrier system (i.e., the engineered parts of the repository and the waste package) of the repository (DOE-OCRWM, 2002b). DOE is setting up a long-term science program (the Systems Performance Enhancement and Cost Reduction program) to operate in parallel with the science program for the license application.

DOE is finalizing the repository design, the operating requirements, and the radiologic safety requirements to be included in the license application. The repository design continues to evolve with time.

Major changes in design have included waste package characteristics (in particular the recent inclusion of a titanium drip shield[4] and a change in container material to the C-22 alloy), an increase of the ventilation rate, and changes in the underground design to accommodate a range of thermal operating modes. The thermal operating mode will be finalized later in the operation phase, depending on the desired maximum post-closure temperatures of the waste package surfaces, the emplacement drift rock walls, the repository rock, and the humidity in the emplacement drifts (DOE-OCRWM, 2001a). The extent to which these changes result from a structured learning process, as advocated in Adaptive Staging, or result from unexpected findings or from external pressures is discussed below.

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[3]The Yucca Mountain site is located about 160 km (100 miles) northwest of Las Vegas, Nevada. The host rock proposed for the potential repository is an unsaturated welded tuff; a unit of the Topopah Spring Member (DOE-OCRWM, 2001a).

[4]The engineered barrier system includes a titanium drip shield installed over the waste packages at the time of repository closure. DOE's rationale for including a drip shields is to keep the waste packages dry for thousands of years, hence reducing the corrosion rate of the waste packages. The titanium drip shield would also protect the waste package from rock falls that could compromise the corrosion barrier of the waste package.

Sidebar F.2 Other Wastes for Yucca Mountain

Radioactive wastes are classified by their origin or radiotoxicity in order to ensure safe handling and disposal. High-level radioactive waste requires deep geologic disposal, while most low-level radioactive waste may be disposed of at or near the ground surface. The United States has an additional waste stream not so highly radioactive as high-level waste but that contains significant amounts of long-lived radioactive materials; transuranic waste from its defense program. This material may be isolated from the biosphere with the high-level waste or in similar disposal facilities. Currently, it is being disposed in a geologic disposal site, WIPP in New Mexico, under a different regulatory system than that which prevails for Yucca Mountain (see Sidebar F.1).

The United States also has commercial nuclear low-level waste that is greater than Class-C (GTCC); it exceeds the limits of low-level waste set for disposal in near-surface licensed sites. These commercial GTCC wastes include transuranic wastes and highly irradiated metals from nuclear reactor core structures, other than the metal parts of the spent fuel assembly, which are considered to be high-level waste. The GTCC classification is not used for low-level waste generated in the DOE complex; all of the DOE low-level waste is the responsibility of DOE. Commercial GTCC wastes are the responsibility of DOE by Section 3(b)(D) of the Low-Level Radioactive Waste Policy Amendments Act of 1985. In revision of its low-level waste regulations the USNRC has ruled at 10 CFR Part 61.55 that "such waste [GTCC] must be disposed of in a geologic repository as defined in Part 60 or 63 of the chapter unless proposals for disposal of such waste in a disposal site licensed pursuant to this part are approved by the Commission." Thus, quantities of these commercial GTCC wastes may be emplaced with the high-level waste at Yucca Mountain.

F.1.3 Licensing

The USNRC is the regulator for the high-level waste repository program in the United States. The USNRC's role in any licensing action is to apply regulations and to review applications for proposed actions to determine compliance. The burden of proof is on DOE to show that the proposed action is safe, to demonstrate that regulations are met, and to ensure continued compliance with the regulations (USNRC, 2002a). The USNRC has set up a sequential licensing process consisting of the following specific licenses or amendments:

1. license to construct the repository,
2. license to receive and emplace waste,
3. license to permanently close the repository, and
4. termination of the repository license.

The Supplementary Information to Title 10 CFR Part 63, reads:

"Part 63 provides for a multi-staged licensing process that affords the Commission the flexibility to make decisions in a logical time sequence that accounts for DOE collecting and analyzing additional information over the construction and operational phases of the repository" (66 Federal Register 55738, November 2, 2001).

The USNRC made a distinction in Part 63 about the level of safety assurance that is obtainable from the use of the performance assessment.[5] This distinction has the effect of dividing the DOE application into two safety cases: one, for pre-closure safety, requires a finding of "reasonable assurance"; the other, for post-closure safety, requires a finding of "reasonable expectation."[6]

The USNRC has a long history of licensing nuclear activities on the basis of a finding that may be stated as "reasonable assurance that the facility has been constructed and will be operated in conformity with the license, the provisions of this Act, and the Commission's rules and regulations" (Atomic Energy Act of 1954, as amended, Section 185.b). The expression "reasonable assurance" has come to indicate the level of assurance a regulator can obtain from pervasive oversight of an activity from beginning to end. The USNRC in addressing comments on the promulgation of 10CFR Part 63 noted that the EPA commented that a connotation has developed around "reasonable assurance" that could lead to an extreme approach of selecting worst case values for important parameters. The EPA believes that "reasonable assurance" is appropriate for operating facilities that operate under active institutional controls during their lifetime. It is not appropriate, in EPA's view, for the licensing of a repository where projections of performance have inherently large ranges of uncertainty. Where such pervasive oversight is not sustainable, as during long-term post-closure performance, a lesser level of assurance is all that can be attained. The USNRC adopted the EPA expression "reasonable expectation" as the level of assurance to be obtained for post-closure performance objectives. The USNRC noted that "confidence that DOE has, or has not, demonstrated compliance with EPA's standards is the essence of NRC's licensing process." The USNRC went on to state its intent to review the full record before it to make the licensing determination (66 FR 55739-55740, November 2, 2001).

In Part 63.31 the USNRC distinguishes the different levels of assurance when it requires that to authorize construction it must determine

(a) Safety,

(1) That there is reasonable assurance that the types and amounts of radioactive materials described in the application can be received and possessed in a geologic repository operations area of the design proposed without unreasonable risk to the health and safety of the public; and

(2) That there is reasonable expectation that the materials can be disposed of without unreasonable risk to the health and safety of the public.

[5]For a definition of performance assessment see Sidebar 5.1 in Chapter 5.

[6]Consistent with the U.S. Environmental Protection Agency's high-level waste standards, the USNRC chose the term "reasonable expectation" rather than "reasonable assurance" in the regulatory context for Yucca Mountain.

Paragraph (a)(1) applies to receipt and possession of the waste; (a)(2) applies to permanent disposal. DOE is currently planning to submit the application for construction authorization in 2004. The USNRC has three years (with a possible 12-month extension) to complete the review of the application and conduct a public hearing.

Prior to receipt of a license application the USNRC conducts pre-licensing consultation with DOE. Although non-binding, this process provides for a public dialogue between the USNRC and DOE to discuss technical and safety issues and to identify paths to resolution. Additionally, the USNRC interprets and enforces the EPA's safety requirements for the repository before the license application, principally through its regulation 10 CFR Part 63 (USNRC, 2001).[7] The USNRC will review each license application submitted by DOE. If the USNRC review ultimately finds the application acceptable, the matter will be put before a USNRC Hearing Board to review contentions from involved parties. The license cannot be granted unless the Hearing Board issues a favorable judgment. Under the terms of the NWPA the USNRC has three years, with a possible one year extension that must come from the Congress, to complete the review and adjudication of the application for construction authorization (NWPA, Sec. 114[d]). A formal review and adjudication are required for each license or amendment.

At each licensing phase the USNRC will ensure that DOE has specified the nature and extent of the performance confirmation program—a program that continues through to permanent closure with the objective of testing and challenging the technical basis for the safety analysis. After a license is granted the USNRC will provide oversight of DOE's operation for construction, for receiving and emplacement of waste, and for closure and termination of the repository license. At the time of the first construction authorization and at each licensing step the USNRC will determine whether the license application is sufficient to demonstrate compliance with USNRC's regulatory requirements.

During the pre-licensing consultation period the USNRC identified 293 key technical issues (USNRC, 2002b) and reached agreement with DOE on its schedule for addressing these issues, some of which require work outside the repository area (e.g., corrosion testing of the C-22 alloy).

F.1.3.1 The USNRC license hearing process

The USNRC has traditionally used an Atomic Safety Licensing Board (ASLB) to hold formal litigation and judgment of the rightness of the licensing action for major actions. Informal hearings, typically with a single administrative law judge, are used for contested minor actions. The USNRC high-level waste regulations have long called for establishment of such an ASLB for all Yucca Mountain licensing actions and amendments. Experience with the potential for delay in licensing proceedings of this type apparently prompted the Congress to impose the schedule requirements in Section 114(d) of the NWPA "that the Commission shall issue a final decision approving or disapproving the issuance of a construction authorization not later than the expiration of 3 years after the date of submission of such application...." These litigations have a formality and process that are different from the processes of a continuing program.

[7]The role of the U.S. Environmental Protection Agency in the Yucca Mountain Project ended in 2001 with the promulgation of the Yucca Mountain standard for radioactive release limits.

In a licensing hearing the ASLB is expected to hear DOE testimony to support its application and safety case as well as testimony to support the USNRC staff evaluation report. Contentions filed by the intervening parties with standing would be argued before the ASLB, with all parties able to cross examine the witnesses. The state is automatically given standing in the proceeding. During the litigation the repository design is "frozen."

After the hearings are concluded and with due consideration the ASLB makes its findings to the USNRC. Depending on the outcome the proposed action may be approved, modified, or denied. If dispute remains, the ASLB ruling can be appealed to the USNRC itself for adjudication. The process can take years to complete but must remain within the three-year constraint imposed by Section 114(d) of the NWPA, unless the USNRC seeks a one-year extension from the Congress under that same section.

F.1.4 Construction

This phase will begin once DOE obtains the USNRC license to construct the repository, and is scheduled to last 4 years. The initial plan was to construct the entire repository continuously while applying for the license to receive and emplace waste after a substantial portion was constructed. The current plan is to adopt a modular design in which the surface and subsurface facilities are built as discrete segments or panels. This modular repository design consists of completing about 10 percent of the emplacement drifts during the initial construction phase (before initiation of waste emplacement), with the remainder of the emplacement drifts being completed during the operation phases.[8]

The proposed repository at Yucca Mountain consists of surface and subsurface facilities to prepare the waste for emplacement, handle low-level waste produced on site and underground facilities to dispose of the waste (for details see DOE-OCRWM, 2002a).

The repository design changed considerably during the history of the Yucca Mountain project. There still are different design options for the surface and underground facilities as of late 2002. For instance, the thermal operating mode of the repository (i.e., above or below boiling temperature of water), waste package design and protection (drip shields), backfill, and the operational strategy of the repository have yet to be finalized.

F.1.5 Operation

Before the beginning of this phase DOE must receive USNRC authorization to take title of defense high-level waste and commercial spent nuclear fuel at generator sites, transport it, and emplace it in the repository.

The purpose of performance confirmation is to confirm (or invalidate) the predicted performance of the engineered and natural barrier systems relative to waste containment and isolation. Throughout its implementation, performance confirmation will include measures to ensure and maintain the repository system's ability to retrieve any of the emplaced waste at any time before closure. This assurance will be accomplished through the use of subsurface facilities to monitor the natural and

[8] For further information on the modular design see DOE-OCRWM (2002c,d).

engineered barriers, the emplacement drift and main drift environments, the rock temperature and moisture regimes, the water inflow into emplacement drifts, waste package integrity, and any seismic activity of the site. The types of performance confirmation facilities will include post-closure test drifts, observation drifts, alcoves, niches, and boreholes. One or a combination of these facilities may be used depending on the requirements for access to the monitored geologic media and on the objectives of the monitoring. The performance confirmation activities will provide data to verify that subsurface conditions and changes resulting from construction and waste emplacement are within predicted limits. The performance confirmation also verifies that the natural and engineered systems and components are functioning as anticipated and intended.

After all waste is emplaced, the repository environment adjusts to its selected thermal operating mode. The current repository design is intended to have the capability to operate over a range of thermal conditions. The thermal operating mode can be varied by changing the spacing of waste packages and by controlling ventilation rates and duration. For the high-temperature configuration the design will allow the repository to be closed as early as 30 years after the last waste package is emplaced. For the full range of thermal operating conditions needed to implement the flexible design approach, the design will allow the repository to remain open, with appropriate monitoring and maintenance, for up to 300 years after final waste emplacement. Preserving the capability of the repository design to remain open for up to 300 years provides the flexibility needed to adopt such thermal management approaches as extended drift ventilation that could prove successful in reducing uncertainties in repository performance. However, this also requires maintaining institutional continuity and oversight.

The repository will be monitored and maintained from the start of waste emplacement and for at least 50 years after the end of waste emplacement until the time the repository is permanently closed. Monitoring includes collecting and analyzing data to confirm predicted repository performance, as well as maintenance of the subsurface facility. The monitoring will be done using sensors that will collect data from waste packages, drifts, and the surrounding rock. Remotely controlled inspection gantries will be used to investigate conditions in the emplacement drifts. When waste emplacement activities are completed and it has been confirmed that the repository will perform as expected, an amendment to the repository license will be sought to close the facility.

The baseline plan does not include an intermediate regulatory decision between license to receive and possess and license to close the repository. DOE will report to the USNRC every 24 months any significant deviations from expected conditions and recommend action. License amendments will be needed for substantial design changes, such as changes in the repository design or in the waste emplacement rate.

F.1.6 Closure and post-closure

The closure process is designed to configure the repository in such a manner that little or no human support will be required to continue to isolate the waste for tens of thousands of years. Before closure a monitoring period is maintained after all the waste has been emplaced. Monitoring includes collecting and analyzing data to confirm predicted repository performance as well as maintenance of the subsurface facility (see Appendix E). During the closure period the implementer emplaces the titanium drip shield, over the waste. Finally, the implementer backfills shafts, ramps, mains, and extension drifts, permanently seals the repository, dismantles surface facilities, and constructs physical barriers such as fences, walls, and other systems preventing access to the site, a well as warning signs, markers, and monuments. Detailed records and information on the repository will be distributed to local, state, and federal agencies for their use in controlling access to the site, thus creating institutional barriers. The actual repository closure and decommissioning activities are currently scheduled to last nine years. After closure, monitoring of the site from the surface can continue for as long as desired.

The stated extended service life of 300 years allows future generations to decide whether it is appropriate to continue to maintain the repository in an open, monitored condition or to close it based on development of their criteria and level of certainty regarding ultimate repository performance. The emplaced waste will be retrieved if performance confirmation activities indicate that the repository is unsuitable for long-term isolation of the waste or if recovery of the waste as a valuable resource is warranted. Retrieval concepts are currently being evaluated.

F.2 How much Adaptive Staging is currently incorporated in the U.S. program?

In reaction to the committee's interim report released in 2002 (NRC, 2002), DOE and the USNRC both expressed the view that the U.S. program is consistent with Adaptive Staging. In the committee's judgment DOE has recognized potential advantages of staging its Yucca Mountain Project repository development program and has, since this study commenced, taken further actions to encourage aspects of Adaptive Staging. The following is a summary *(in italics)* of the information provided by DOE and the USNRC (Williams, 2002; Federline, 2002) to describe staging aspects of the program, together with the committee's comments. The committee's overall assessment is reported in Chapter 5, Section 5.2.

Both DOE and the USNRC reported to the committee that the U.S. program's decision-making process is characterized by decisions at stable, well-defined points having logical links to the safety case. This is an approach with a primary objective of increasing safety and reducing uncertainties. DOE updated twice its safety analysis for the Viability Assessment and Site Recommendation. The precedent at the Waste Isolation Pilot Plant (see Sidebar F.1) suggests periodic performance assessment updates during operation. Moreover, the USNRC regulations require:

- *a safety assessment for license application for construction,*
- *an updated safety assessment based on information obtained during construction to support license to receive and possess, and*
- *an updated safety assessment based on performance confirmation data for the application for a license amendment to close the repository.*

The committee perceives the U.S. program's roadmap as being largely characterized by a single predetermined path to a defined end point in which stages are defined principally as milestones driven by cost and schedule. These milestones correspond to the minimum stages required by the statute and the regulations for

USNRC licensing. For instance, it appears that there are no intermediate decisions between license to receive and emplace waste and repository closure.

The committee is concerned as to whether there will be any re-evaluation of the safety case during the operational phase.[9] The roadmap is re-evaluated only if compelling new evidence requires it (i.e., if parties external to the program or the regulator raise concerns). While it is true that the roadmap has adapted with time, the adaptations were mostly triggered by external events, as detailed at the end of this section.

DOE and the USNRC believe that the U.S. program matches the attributes of Adaptive Staging:

- *Commitment to systematic learning. The performance confirmation program defines a systematic learning path with a primary objective toward challenging the safety case with the goal of increasing confidence.*

The committee believes that the learning aspect has been underemphasized. DOE tends to give the message prematurely that everything is known in sufficient detail. The positive results of being able to introduce changes into the program are not built into the basic approach; in other words, DOE relies on Linear Staging. Accordingly, each time DOE changes the baseline roadmap or the repository design it is strongly criticized by some stakeholders. DOE has not set appropriate expectations with stakeholders about the need for systematic learning, that can lead to changes.

- *Flexibility. The U.S. repository program allows opportunities for safety enhancements or cost benefit changes consistent with safety. The USNRC process of license amendments and license conditions[10] provides flexibility for changes for the enhancement of safety that are available for public review. A requirement in Part 63.44(c)(2) instructs DOE to report to the USNRC every two years on changes, tests, and experiments that were made or conducted without amendment.*

The committee agrees that opportunities for flexibility are available. More specific details on the interactions between DOE and USNRC that would allow this flexibility to be used in the licensing phases are discussed in Section 5.4.2.

[9]The committee acknowledges that the USNRC requires DOE to submit reports every 24 months with new information; however, this information does not necessarily trigger a revision of the safety case.

[10]A license condition is not a partial license. The English usage of "condition" in the licensing context is the same as use of the word for conditions of a contract (i.e., terms that must be satisfied to satisfy the contract). The USNRC does not define the term in its regulations, but it does state in 10 CFR 72.44(a): "(a) Each license under this part shall include license conditions. The license conditions may be derived from the analyses and evaluations included in the Safety Analysis Report and amendments thereto submitted pursuant to 72.24. License conditions pertain to the design, construction and operation. The Commission may also include additional license conditions as it finds appropriate "

- *Reversibility. The USNRC requires DOE to preserve the option to retrieve the waste for 50 years after initiation of waste emplacement.*

The committee's understanding of reversibility goes far beyond this regulatory requirement. Retrievability is only one aspect of reversibility; it is, however, important to maintain and demonstrate its feasibility until the repository is closed. Equally important is that reversibility, either totally or at least to a lesser degree such as design change, must be considered as an option at each stage (see Fig. 2.1a). We hope the probability of reversal decreases with time. DOE provides another prominent example of reversibility:

- *With Congress, reversibility of policy is always an option. Examples of congressional control are:*
  -Development of controlling legislation (NWPA, NWPAA, National Energy Policy Act of 1992).
  -State veto override process.
  -Annual appropriations (which often contain program direction), such as:
    - *FY 1994—blocked funding of grants for feasibility studies for potential volunteer sites for a federal storage facility.*
    - *FY 1996—report language directed DOE to focus on scientific issues related to suitability and to delay work on license application.*
    - *FY 1997—directed submission of Viability Assessment.*

The committee recognizes these as opportunities for the Congress to reverse the program. However, the spirit of Adaptive Staging is that all parties acknowledge throughout the program that reversibility is always a possibility to consider before moving to the following stage. Moreover, reversibility should be driven by knowledge not by politics or cost.

- *Transparency, auditability, and integrity. DOE points out that transparency, auditability, and integrity are ensured in the U.S. program through the regulatory process, federal control, Congressional policy, and technical oversight, as well as through public involvement. This is illustrated by the following examples:*
  -The USNRC formal review process provides an auditable and transparent record of the safety case and the regulatory decisions on contested issues. The independence of the regulator is the foundation for the integrity of the process.
  -The U.S. program, as a federal program, is subject to transparency and auditability requirements, the purpose of which is to ensure the integrity of the program. Examples of transparency and auditability requirements are the Freedom of Information Act, Federal Advisory Committee Act, and the Administrative Procedures Act. Many program documents and available directly on the Internet.
  -The NWTRB, the statutory oversight board, has access to all draft and final documents by law.
  -The Office of Management and Budget and the Congress provide policy oversight and control the program through funding allocations. Budget and justification are made public in the President's budget.

-Opportunities for public involvement are included at each stage of the program in several ways:

- *The USNRC provides opportunities to the public to participate in dialogue and to provide comments on all pre-licensing issues. There will also be formal opportunities for public involvement in the licensing hearing process.*
- *The public was involved in development of the NWPA through the following channels:*
  - *a) Interagency Review Group was composed of 14 agencies and held multiple hearings; 15,000 copies of draft were circulated and 3,300 comments were received. This review group considered strategies ranging from proceeding with repository in salt to delaying until alternatives to geologic disposal were developed.*
  - *b) Generic Environmental Impact Statement process. Alternative disposal technologies were considered.*
  - *c) The EPA workshops on repository regulation.*
  - *d) Extensive interest group participation occurred in NWPA hearings from 1978 through passage in 1982, including inputs from several groups.*
- *The public was involved in the development of DOE, USNRC, and EPA regulations under the Administrative Procedures Act.*
- *The State of Nevada and affected units of government receive funds for program oversight; in particular, the Nye County science program is providing input to the program. Nevada has the right to a negotiated "consultation and cooperation" agreement with DOE; Nevada can provide inputs at identified key events, milestones, and decisions. The agreement allows binding arbitration for dispute resolution. DOE observes that the State of Nevada has not availed itself of the opportunity.*
- *Extensive hearings and opportunities to review and comment on program documents were offered during the Environmental Impact Statement and site recommendation process.*
- *The public has direct influence through congressional representatives, for instance, through the state veto override process and through the annual appropriations process.*
- *NWTRB meetings offer opportunities for public comment.*

The committee shares the opinion that the U.S. program is one of the most open waste management programs worldwide. The volume of information available to the public is impressive, and efforts are made to communicate the information. However, the improvements that might be made to the program go beyond simply providing data to the stakeholders. Resulting data for all programs would be made available. Important also is that the justification for choosing the specific investigation areas is made accessible for review and comment.

Not all decisions have been transparent. For example, adoption of the titanium drip shield was a development that took place suddenly and without much external discussion. Other decisions in the program that do not correspond to the principles of Adaptive Staging have sometimes been taken out of the hands of DOE. In the 1987 amendment to the NWPA the Congress narrowed the process, directing DOE to terminate activities on or about other sites and concentrate only on characterization of Yucca Mountain. This pragmatic narrowing to one site lost one of the desirable aspects of Adaptive Staging: maintaining alternative choices; the decision made by the Congress placed alternative site choices in sequential order rather than parallel.

The committee listened to public views expressing the opinion that the communication from DOE continued to be too one-sided. There was a perception that DOE was not acting on what was heard. In addition, there was no mechanism for stakeholder and public input into decision-making.

Much of the controversy surrounding the Yucca Mountain project has revolved around the lack of cooperation between DOE and the State of Nevada. The committee recommends in Chapter 6 that the state participate in the creation of a technical oversight group and a stakeholder advisory board. DOE has expressed willingness to support this and the state has so far refused to participate.

- *Responsiveness. The USNRC process requires responsiveness to new information at key decisions and timely consideration of any information with significant safety implications. This information is also provided to the stakeholders in a timely manner. As an example of responsiveness, the program is now addressing the 293 key technical issues raised by the USNRC. Other examples of responsiveness are the following major changes in the program in response to recommendations by the NWTRB:*
  - *-adoption of robust, long-lived engineered barriers,*
  - *-use of tunnel-boring machine instead of drill and blast,*
  - *-excavation of the cross drift in the Exploratory Studies Facility,*
  - *-evolution to flexible design to preserve low-temperature option suggested by NWTRB, and*
  - *-implementation of an independent review of age of fluid inclusions.*

The committee recognizes that DOE has often responded to external input by amending its program. For example, Evolution to a modular repository design was triggered by budgetary concerns and accelerated by the committee's progress report. According to DOE the initial incentives for implementing a modular repository design were to reduce initial investment and to waste emplacement. Development of a flexible thermal operating mode was triggered by concerns repeatedly expressed by the NWTRB (2002).

The viability assessment was introduced as a useful intermediate stage on the way to site-suitability determination. Again, the reason was external: primarily that DOE faced reduced funding for fiscal year 1996 and was instructed by the conference report accompanying the appropriations act to concentrate the repository effort on the major unresolved technical questions posed by the USNRC. The Site Characterization Plan was submitted to USNRC in late- 1988; the USNRC provided extensive comments and two significant objections in mid-1989. The two objections argued that (1) DOE did not have adequate quality assurance for gathering and retaining site- characterization data and (2) DOE did not have an adequate repository design control process. The viability assessment was completed and reported in 1998. The viability assessment represented a new stage that was not contemplated in the initial roadmap.

The external input appears not to have been gathered through a systematic learning and decision-making process but rather was perceived as a potential "showstopper" that had to be addressed. Addressing the 293 key technical issues is not an example of Adaptive Staging's responsiveness, because it is imposed on DOE by the USNRC to obtain a license. DOE plans to address (not resolve) all key technical issues by 2004, the date of the submission of the license application. Adaptive Staging would not presume, without good justification, that the key technical issues could be addressed by a fixed date. An example of the more difficult key technical issue concerns the corrosion rate of C-22 alloy. Adaptive Staging may alter resolution of a key technical issue and alter the repository design itself. The committee acknowledges that DOE is under pressure to address these key technical issues within a specific time frame in order to file a complete application.

However, the committee believes that with Adaptive Staging, DOE would be better positioned to formalize the learning process and to address broader technical and societal issues while building stronger public trust.

References

DOE-CAO (Department of Energy, Carlsbad Area Office). 1996. Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184. Carlsbad, N. Mex.

DOE-OCRWM (Department of Energy, Office of Civilian Radioactive Waste Management). 2001a. Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program. DOE/RW-0533. Washington, D.C.: U.S. Department of Energy.
Available at: http:// www.rw.doe.gov/tslccr1.pdf.

DOE-OCRWM. 2001b. Civilian Radioactive Waste Management System Total System Description Revision 02 (TDR-CRW-SE-000002). DOE/RW-0500. U.S. Department of Energy.
Available at: http://www.rw.doe.gov/tsdkrb/tsdkrb.htm.

DOE-OCRWM. 2002a. Yucca Mountain Science and Engineering Report. Technical Information Supporting Site Recommendation Consideration. Revision 1. February 2002. DOE/RW-0539-1.
Available at: http//www.ymp.gov/documents/ser_b/front.pdf.

DOE-OCRWM. 2002b. The Yucca Mountain Project. Project Operations. Available at: http://www.ymp.gov/toc/functional/func.htm.

DOE-OCRWM. 2002c. Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-0250. February 2002.
Available at: http://www.ymp.gov/documents/feis_a/index.htm.

DOE-OCRWM. 2002d. Modular Construction System Evaluation. Pre-Decisional Study. TDR-CRW-SE-000023 REV 00. August 2002. Prepared by Bechtel SAIC Company LLC. Washington, DC: Department of Energy.

Federline. M. 2002. USNRC's Feedback on Committee's Interim Report. Presentation before the committee. June 10. Washington, D.C.

NRC (National Research Council). 1957. The Disposal of Radioactive Waste on Land. Washington, D.C.: National Academy Press.

NRC. 1996. The Waste Isolation Pilot Plant: A Potential Solution for the Disposal of Transuranic Waste. Washington, D.C.: National Academy Press.

NRC. 2001a. Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant. National Academy Press. Washington, D.C.: National Academy Press.

NRC. 2001b. Disposition of High-Level Waste and Spent Nuclear Fuel. The Continuing Societal and Technical Challenges. Washington, D.C.: National Academy Press.

NRC. 2002. Principles and Operational Strategies for Staged Repository Systems: Progress Report. Washington, D.C.: National Academy Press.

NWPA (Nuclear Waste Policy Act). 1982.
Available at: http://www.rw.doe.gov/progdocs/nwpa/nwpa.htm.

NWTRB (Nuclear Waste Technical Review Board). 2002. Letter report to Congress and the Department of Energy. January 24. Washington, D.C.

University of New Mexico. 2001. Institute for Public Policy, Public Opinion Profile of New Mexico Citizens. Focus on WIPP. Report for Fall 2000/Spring 2001. Public Opinion Profile of New Mexico Citizens 13(1).
Available at: www.unm.edu/instpp.

USNRC (U.S. Nuclear Regulatory Commission). 2002a. Yucca Mountain Review Plan. NUREG-1804. Rev. 2. USNRC March.

USNRC. 2002b. List and Status of Key Technical Issues for High-Level Waste.
Available at: http://www.nrc.gov/waste/hlw-disposal/reg-initiatives/list-status-kti.html.

Williams, J. 2002. DOE's Vision of Staging. Presentation before the committee. June 10. Washington, D.C.

Appendix G

Glossary

Adaptive Staging: a flexible decision-based process in which stages are predicated on the outcome of previous ones and are separated by Decision Points.

Backfill: material used to refill excavated portions of a repository after waste has been emplaced.

Buffer storage: a surface facility that acts as a "capacitor" giving flexibility in timing the transfer of any goods on to the next step in a process. This area receives waste, holds it, and blends it before underground emplacement.

Decision Point: the re-evaluation period that separates stages within a phase of geologic repository development. Decision Points provide the opportunity to integrate newly acquired knowledge into the program, evaluate the program's status, and decide how to proceed. Decision Points focus the implementer on identifying program improvements with respect to, for instance, environmental impact, safety, cost, and schedule.

Demonstration activities: activities performed by the implementer to illustrate in particular to other stakeholders and the public, that the chosen repository design and operating mode does indeed perform as expected. Demonstration activities start only after defining the reference configuration (i.e., after the pilot activities conclude) and continue through repository closure. Direct demonstration of long-term safety is, of course, not feasible.

Demonstration facility: dedicated area in the as-built repository but with added measures for monitoring. Demonstration facilities may be a part of the main disposal area or may be in separate but still representative areas to allow intensive monitoring without compromising the integrity of the repository.

High-level waste (HLW): radioactive material emitting high doses of ionizing radiation representing a health hazard for very long times into the future unless measures are taken to isolate it from the human environment. In this report high-level waste refers to commercial spent nuclear fuel, naval spent nuclear fuel, defense-related high-level waste, highly enriched uranium, and plutonium. Key characteristics of these materials are (1) the type of radiation emitted, (2) the rate at which the intensity decreases with time, and (3) the ease with which the material can be misused in nuclear weapons.

Implementer: the agent, either an agency of the government or a private company, that locates, develops, and operates the geologic repository.

Interim storage: any surface storage that is decoupled from emplacement (i.e., storage can be for an open-ended time) and does not require that there be an operating repository.

Linear Staging: management process characterized by a single path in which stages are defined primarily by milestones driven by program schedule and cost.

Long-term science and technology program: an ongoing program to improve the scientific understanding of the geologic repository system. The program includes scientific activities to (1) update the safety case, (2) investigate engineering alternatives to optimize repository design, and (3) and confirm (or invalidate) previous assumptions, data, and analyses.

Monitoring program: sampling programs to measure and record conditions and temporal changes in parameters relevant to the repository program. These parameters may be the physical and chemical indicators of repository behavior and of its surroundings or social science indicators of public beliefs, concerns, and attitudes about the repository project.

Oversight body: advisory groups not mandated by legislation that advise and guide implementers and regulators.

Performance confirmation program: program to test, evaluate, and confirm that the repository system (at the site, elsewhere in the field, or in the laboratory) and its natural environment are behaving as expected and within acceptable safety margins.

Phase: a primary element of repository development: selection of a geologic disposal option, site selection and characterization, licensing, construction, operation, closure, and post-closure. Multiple stages and the Decision Points that separate each stage constitute a phase.

Pilot activities: preliminary tests of alternative repository designs and operating modes carried out in configurations increasingly close to those foreseen for the final repository. The objective is to learn about the system and processes under realistic conditions and then apply this learning to finalize the chosen design and operational procedures. Pilot activities at the repository site can begin with nonradioactive material and continue with radioactive waste when the license to operate the repository is obtained. Normally pilot activities cease with the transition to full-scale operation, but late introduction of a major new emplacement technology, for example, could be preceded by pilot activities.

Pilot facility: a facility that hosts pilot activities. Pilot activities concerning the engineering barriers (e.g., canister sealing) may take place in any laboratory or workshop facility. Pilot facilities specific to the repository are located within the repository's footprint in one or more dedicated disposal tunnels or drifts.

Reference framework: the path for developing a successful geologic repository with Adaptive Staging. The reference framework is based on the best scientific and societal knowledge available at a given time. The reference framework includes, for instance, a reference repository design and a proposal for stages and a decision-making process. The framework is not a rigid roadmap attempting to define all future activities to successful project implementation. At the end of each stage the details of the reference framework may be adapted (i.e., the repository design and number of Decision Points may change) according to knowledge gathered along the way.

Regulator: agencies, usually identified by national legislation, that set standards and criteria for developing and operating the repository and assure adherence to these standards.

Repository program: the program that organizes the operation, closure, and post-closure phases of a geologic repository.

Repository system: system including the geologic repository as well as transportation and interim (surface) storage programs.

Retrievability: the possibility of reversing the action of waste emplacement. It is thus a special case of reversibility.

Reversibility: a distinct option to abandon an earlier decided-upon path and reverse the course of action to a previous stage if new information warrants.

Safety case: a collection of arguments, repeated and reaffirmed at stages of repository development, in support of the long-term safety of the repository. See Sidebars 2.1 and 5.1 in Chapters 2 and 5, respectively.

Stage: a part of a phase in geologic repository development that concludes with a Decision Point.

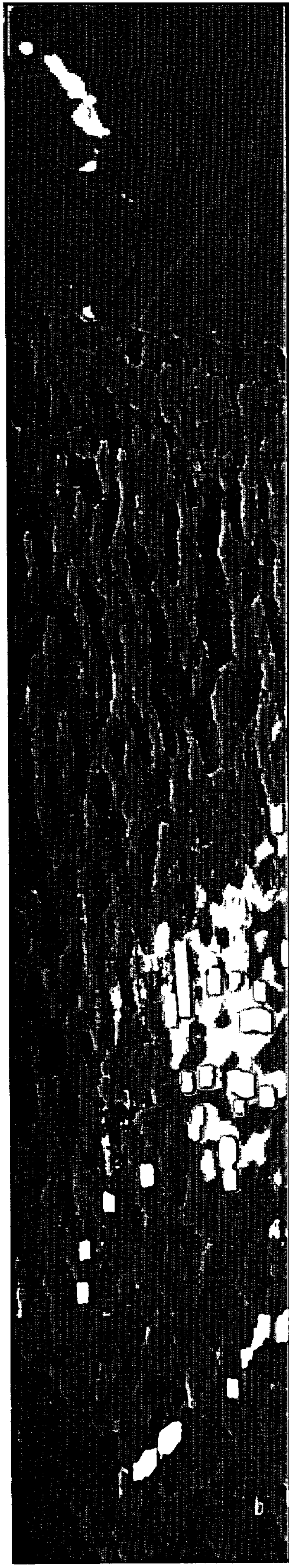
Stakeholder: see Sidebars 3.2 and 5.2 in Chapters 3 and 5, respectively.

Test activities: scientific tests to learn about the performance of a geologic repository. Tests activities begin early (i.e., before concept or site are finalized) and continue until no further significant learning occurs.

Test facility: a facility hosting test activities. To ensure that tests are relevant the facility is located in an environment similar to the repository environment (i.e., in the same host rock), but it may be physically separate from the actual disposal area to ensure that the tests, which can go beyond design expectations, do not compromise the repository integrity.

Thermal blending: selecting for emplacement in the repository waste packages with differing heat output, and thus determining the temperature distribution in the repository throughout the repository lifetime.

Thermal operating mode: mode of operation of the underground facilities with respect to the temperatures of drift walls and waste packages, as well as relative humidity. In a higher-temperature operating mode the temperature of the average waste package would rise significantly (over 160°C) after the repository is closed. In a lower-temperature mode the waste package surface temperature would be kept much lower (approximately 85°C).



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