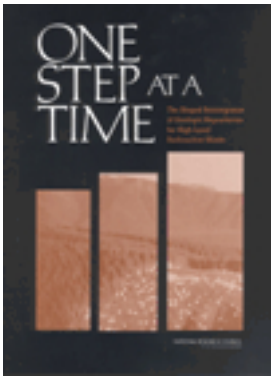
Free Executive Summary



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, National Research Council

ISBN: 978-0-309-08708-7, 216 pages, 8 1/2 x 11, paperback (2003)

This book focuses on a management approach called "adaptive staging" as a promising means to develop geologic repositories for high-level radioactive waste such as the proposed repository at Yucca Mountain, Nevada. Adaptive staging is a learn-as-you-go process that enables project managers to continuously reevaluate and adjust the program in response to new knowledge and stakeholder input. Advice is given on how to implement staging during the construction, operation, closure, and post-closure phases of a repository program.

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 im-

provements 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.

[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

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[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.

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

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

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.

International Standard Book Number: 0-309-08708-2

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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.

Printed in the United States of America

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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

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