Managing Spent Nuclear Fuel

Strategy Alternatives and Policy Implications

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Preface

About This Document

Increasing the fraction of nuclear power in the mix of electric power-generation technologies is one approach to reducing emissions of greenhouse gases. A major roadblock to investment in new nuclear power plants in the United States is uncertainty about the fate of spent nuclear fuel. If nuclear power is to be a sustainable option for the United States, methods for managing spent nuclear fuel that meet stringent safety and environmental standards must be implemented. This monograph evaluates technical approaches, institutional factors, and strategy options for managing spent nuclear fuel and draws policy implications associated with different societal priorities and values.

On January 29, 2010, the U.S. Secretary of Energy established the Blue Ribbon Commission on America's Nuclear Future to provide recommendations for managing spent nuclear fuel and other nuclear wastes. We intend this monograph to be of interest to commission members and staff, as well as other stakeholders in the spent–nuclear fuel policymaking process.

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Summary

Nuclear power provides an alternative to coal and natural gas–fired electric power generation that emits far fewer greenhouse gases. As such, increasing nuclear power generation is one approach to reducing emissions of greenhouse gases. However, while nuclear power provides about 20 percent of electricity generated in the United States, no construction of nuclear power plants has begun since 1977. One of the major impediments to increasing nuclear power is the decades-long impasse over how to deal with spent nuclear fuel.

Until 2009, national policy for the management of spent fuel was guided by the path laid out in the 1982 Nuclear Waste Policy Act (NWPA), as amended: Under this act, utilities producing spent nuclear fuel have the option to transfer ownership of the spent fuel to the federal government, which will ultimately dispose of it in a permanent geological repository. The repository would isolate the spent fuel from the environment until it no longer poses a safety or health risk. The federal government was required to be able to take title to the spent fuel in 1998, when the repository was to have been licensed and ready to receive the spent fuel and other wastes from defense activities. In 1987, the NWPA was amended to require that the U.S. Department of Energy (DOE) consider only Yucca Mountain, Nevada, as a candidate for the nation's first repository, eliminating consideration of other candidate sites and provisions for selecting a second repository site, as envisioned in the 1982 NWPA.

To date, all commercial spent fuel remains at nuclear power plants and, despite more than 20 years of effort, the Yucca Mountain repository has not been built or licensed. Several utilities have filed lawsuits against the federal government claiming compensation for costs to store spent fuel after the 1998 deadline. In 2009, the administration eliminated funding for Yucca Mountain, and DOE subsequently filed a motion to withdraw its license application with the Nuclear Regulatory Commission. The cessation of efforts to pursue the Yucca Mountain repository indicates the need for a major policy review. In January 2010, the U.S. Secretary of Energy established the Blue Ribbon Commission on America's Nuclear Future to provide recommendations for managing spent nuclear fuel and other nuclear wastes.

If nuclear power is to be sustainable and accepted by the public, the nation must agree upon a solution to the spent–nuclear fuel problem that convincingly meets safety

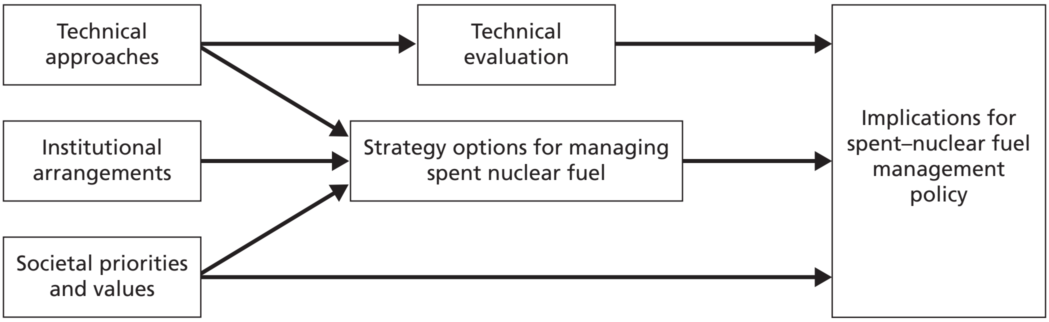
and environmental standards. What are the alternatives for safely managing, storing, and disposing of spent nuclear fuel, and how can they be characterized in a way that provides a better understanding of the trade-offs and policy implications of the alternatives?

There is an international consensus that no existing or currently conceived future technology can eliminate the need for one or more geological repositories for long-lived radionuclides. Permanent geological disposal does not need to occur immediately, however, and technical options exist that can buy time for an incremental approach to repository development and possibly also change the characteristics of the waste.

The objective of this monograph is to review the current status of the main technical and institutional elements of spent–nuclear fuel management and to identify the implications for the development of spent-fuel management policy. We examine policy implications in the context of a range of possible strategic approaches. While the strategies considered span much of the range of options currently being considered, we do not comprehensively evaluate all policy options nor attempt to recommend a particular policy approach. Due to the limited time available for this research, we chose to focus on commercial spent fuel exclusively and not to deal with the additional question of the disposition of defense nuclear waste.

The approach we follow is summarized in Figure S.1. Analysis of the key technical approaches and institutional arrangements associated with spent–nuclear fuel management, along with consideration of societal preferences, leads to a set of strategy options. The strategy options are then compared in the context of the technical evaluation and societal preferences to elucidate implications for spent–nuclear fuel management policy.

Figure S.1
Summary of Analytical Approach



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Technical Approaches to Spent–Nuclear Fuel Management

We examine four categories of technical approaches that comprise the essential approaches of any long-term strategy for spent–nuclear fuel management:

- surface storage technologies at existing nuclear plant sites (on-site storage)
- centralized interim storage away from plant sites
- advanced fuel cycles with spent-fuel recycling
- permanent disposal in a deep geological repository.

Any strategy for managing spent nuclear fuel will be built around combinations of these options, and all strategies must ultimately include permanent geological disposal.

To better understand these approaches, we consider them first as stand-alone technologies. We apply five criteria that cover many of the key concerns about nuclear power voiced in public debates and in the academic literature: safety, security, technical obstacles, public acceptance, and cost. Focusing initially on impacts over the next 20 to 30 years, we summarize the results of our evaluation of each approach in Table S.1. The evaluations are necessarily qualitative, and there is considerable uncertainty tied to them. The intention is to identify major distinctions between the approaches for each criterion when these technologies are viewed in isolation and relative to ultimate disposition of spent fuel or its derivatives in a geological repository.

In the case of advanced fuel cycles, we also examined the potential impacts on capacity requirements and environmental risk for a geological repository and uranium resource requirements.

Table S.1
Evaluation of Technical Approaches to Managing Spent Nuclear Fuel

Criterion	Continued On-Site Storage	Centralized Interim Storage	Advanced Fuel Cycle	Permanent Geological Disposal
Safety risk	Low	Low	Uncertain	Low
Security risk	Low	Low	Uncertain, potentially low	Low
Technical obstacles	Low	Low	High	Moderate
Public acceptance challenges	Moderate in general, but higher at decommissioned sites	Low near nuclear power plants, but likely to be higher near interim storage sites	High at site-specific level and likely high unless permanent geological disposal resolved	High at site-specific level, but much lower nationally
Cost	Low	Low	High	Moderate

Important findings from our analysis of technical approaches are as follows:

- In most cases, there is no pressing urgency to remove spent fuel from nuclear power plant sites—on-site storage is safe, secure, and low cost, and space limitations are generally minimal. An exception is "stranded fuel" at decommissioned reactor sites, where removing the spent fuel would allow redevelopment of the site.
- Centralized interim storage is anticipated to be similarly safe, secure, technically straightforward, and low cost.
- Advanced fuel-cycle technologies are in the early research stage, and implementation will require several decades of substantial funding before they could become viable at a commercial scale.
- Some advanced fuel-cycle configurations have the potential to significantly reduce geological repository capacity requirements (though this gain will be partially reduced by an increase in radioactive process wastes) but will have little benefit in terms of reducing a repository's long-term safety and environmental risk.
- Technical obstacles to developing a permanent geological repository that meets current regulatory requirements are likely to be surmountable; however, past experience shows that public acceptance and trust in the organizations charged with implementing a technological solution might be more challenging.

Institutional Issues

We evaluate the capacity and performance of the current institutional framework beyond the simple question of success or failure in siting a repository with the aim of establishing a baseline against which to consider the value of change. We employ two categories of factors for this evaluation:

- organizational competence and capacity
- performance of decision processes.

In the context of the national policy of siting a permanent repository, our assessment indicates that DOE, the Environmental Protection Agency (EPA), and the Nuclear Regulatory Commission (NRC) have largely performed as Congress directed them to—albeit at a much slower pace than originally anticipated, incurring vastly higher costs, and with some large procedural and technical errors. What mattered more in terms of outcomes were (1) the collapse of the original NWPA consensus for an eastern and western repository and the consequent sole focus on Yucca Mountain; (2) poorly aligned incentives and institutional conflicts of interest that led to a loss of public confidence and gridlock; and (3) the overarching policy under which these agencies labored of driving toward repository siting at the expense of a more comprehensive plan for aboveground, long-term storage and a more incremental approach to repository development.

Moving forward, changes in the institutional framework need to be carefully considered in the context of national policy on management of spent fuel. However, according to our analysis, two major institutional changes merit closer examination to determine whether they would facilitate whatever course of action Congress and the administration choose to pursue, including maintaining the status quo:

- reconsideration of ownership of spent fuel and financing of expanded on-site storage facilities in the absence of a permanent geological repository
- reassessment of organizational responsibilities for managing spent-fuel resources.

All spent-fuel management strategies require utilities to maintain and expand on-site storage for an extended duration. As such, the government's liability for failing to take possession of spent fuel at operating and decommissioned plants will continue to mount unless some change in policy or practice is made. The federal government cannot unilaterally change the terms of the contracts with the utilities with regard to waste acceptance. However, changes in the NWPA could be implemented that would offer utilities an alternative approach to funding long-term on-site storage and, at the same time, would relieve the government of the obligation to take title to the spent fuel immediately. Under an arrangement with strict NRC regulation, the government would place the funds required for long-term storage into separate interest-bearing escrow accounts for each power plant. Utilities would continue to own the waste, but they would also gain control of the funding and have incentives to manage waste storage efficiently, including transport from decommissioned to still-operating plants. Changing this one area of the law would provide the government and industry with significantly more flexibility and potential cost savings than presently exists, and remove a significant impediment to strategies that require more time for research, development, and implementation.

These changes in funding and managing on-site storage might be necessary but still insufficient to fully resolve the waste acceptance issues. For this approach to be feasible, the public and the industry are likely to still need credible assurances in law that progress will be made toward the federal government taking ownership and possession of spent fuel over the next several decades through dedicated funding and transparent, sustainable, and competent organization and management. To further mitigate the effects of eroded public trust and of poorly aligned incentives within the existing framework, it is likely that any new spent-fuel management strategy will have more credibility if it is managed by a new organization outside of DOE. Such an organization could take several forms: public, private, or a public-private hybrid like, for example, a public corporation.

Policy Implications

The recent termination of funding and DOE's effort to withdraw its license application for Yucca Mountain reflect the realization that spent–nuclear fuel management policy in the United States needs to be reexamined. For moving forward, we consider four policy strategies built from combinations of the technical approaches. Each strategy would ultimately lead to the siting and licensing of a permanent repository, but the strategies differ on when and how that goal would be reached. In Table S.2, we identify these strategies by their key near-term (five to ten years) actions related to storage, fuel recycling, and disposal.

Each strategy differs in its focus and concentration of resources in the near term. In any strategy, on-site storage will continue for at least the next decade, and, in some strategies, it might continue for many decades. Although it is impossible to predict timescales with confidence, past experience and the current state of technology suggest that licensing Yucca Mountain or a centralized interim storage facility would take at least a decade, a new permanent geological repository would take two or more decades, and implementing advanced fuel cycles would take many decades. Moreover, even after the capacity for centralized storage, disposal, or recycling becomes available, it will take decades to complete the shipment of spent fuel currently stored at nuclear power plant sites.

The proposed strategies are not intended to represent a comprehensive menu of options but rather were chosen to span a range of approaches and to elucidate some important policy implications of different approaches. To help inform policy deliberations, each strategy is examined in terms of the societal priorities for spent-fuel man-

Table S.2
Strategies for Spent–Nuclear Fuel Management

	Near-Term Actions Related to		
Strategy	**Storage**	**Recycling**	**Disposal**
Expeditiously proceed with Yucca Mountain	Maintain on-site storage until Yucca Mountain available	Maintain current level of advanced fuel-cycle research	Open Yucca Mountain
Develop centralized interim storage in conjunction with permanent geological disposal	Develop centralized storage facilities	Maintain current level of advanced fuel-cycle research	Pursue alternative sites
Pursue advanced fuel cycles	Continue expansion of on-site storage or develop centralized storage facilities	Aggressively expand advanced fuel-cycle development efforts	Do not commit to any particular time plan or site
Maintain extended on-site storage	Continue expansion of on-site storage	Maintain current level of advanced fuel-cycle research	Do not commit to any particular time plan or site

agement that would need to prevail in order for it to be favored, the implications for the welfare of future generations, and the implications for the future of nuclear power in the United States.

Spent-Fuel Management Priorities That Would Favor Different Strategies

The different policy alternatives can have widely differing implications in terms of societal priorities for spent–nuclear fuel management. If the view that we are obligated to provide the capability to dispose of spent fuel as quickly as possible prevails as a top priority, because we believe either that disposal should not be left for the future or that we need to demonstrate the feasibility of the entire fuel cycle before undertaking further development of nuclear power, then proceeding with Yucca Mountain is the best choice. This strategy would also fulfill the federal government's obligation to take possession of spent fuel and pave the way for the expansion of nuclear power. If the main priority is more oriented toward enabling the expansion of nuclear power and a premium is placed on confidence in the decision process related to repository development and performance, then the staged strategy that combines centralized interim storage and siting a new permanent geological repository would be more attractive. Strong support for a very large increase in nuclear power, which could ultimately place a premium on repository capacity and uranium resources, would favor recycling spent fuel with an advanced fuel cycle. Finally, if the prevailing view is that uncertainty regarding repository performance, safety, security, cost, or public and political acceptance of nuclear power looms large enough, then continued on-site storage might be appropriate.

Implications for Future Generations

The strategy alternatives have widely differing implications in terms of trade-offs of responsibilities between current and future generations. A clear distinction is that the different strategies reach different states in terms of progress toward final disposition of spent fuel. Proceeding with Yucca Mountain or the staged storage-repository strategy provides a solution for final disposal in the relatively near term. Depending on the details of the technology chosen, pursuing advanced fuel cycles could leave future generations with significantly decreased repository capacity requirements. However, a substantial investment over an extended duration and with a highly uncertain outcome would be needed to realize those benefits, and other waste products generated from the processes might require deep geological disposal as well. Continued on-site storage leaves the entire burden of disposal for the future.

A related distinction is the level of uncertainty left for future generations. The Yucca Mountain and storage-repository strategies leave the least uncertainty. Pursuing the advanced fuel-cycle alternative would provide future generations with more information on the viability, safety, and security of this approach. But if this is done at the expense of pursuing centralized storage or a permanent repository, future generations will have less information than might be desirable to implement these more-conventional and more-likely options. Also, given the different potential approaches and objectives of advanced fuel-cycle technologies, it is not a given that this strategy would ultimately provide large benefits in terms of reducing repository requirements. Maintaining continued surface storage prolongs the existing uncertainty about how best to manage spent nuclear fuel.

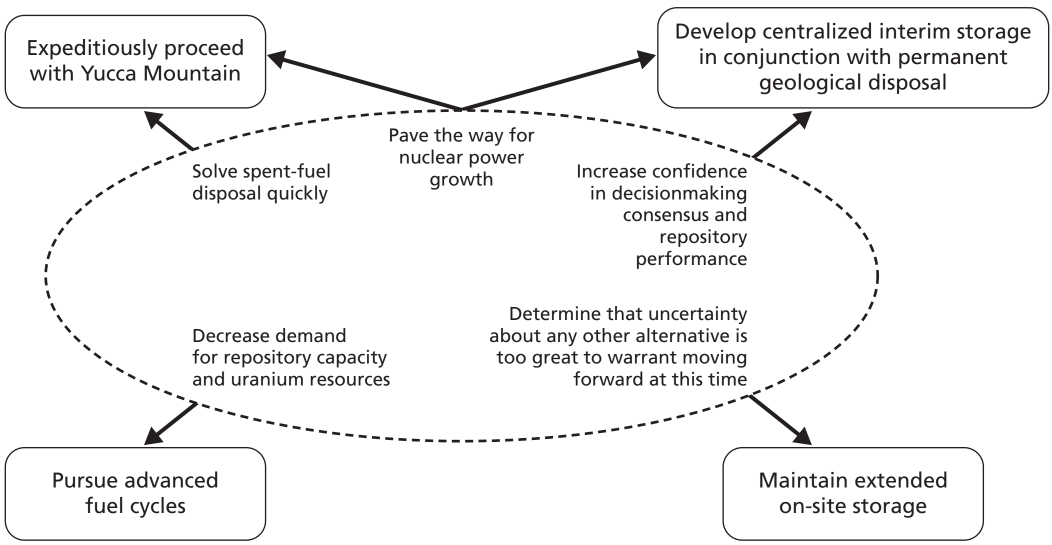
Implications for the Future of Nuclear Power

Expeditiously proceeding with the licensing of a repository at Yucca Mountain and the storage-repository strategies would have the greatest positive impact on the future of nuclear power because they would most swiftly allow the federal government to fulfill its contractual obligation to take possession of spent nuclear fuel now owned by the utilities. This would remove impediments to growth based on spent-fuel concerns. The advanced fuel-cycle strategy could help clear the way for new nuclear power plant development if it included mechanisms to improve the terms for ownership and financing of continued surface storage of spent fuel. Finally, in prolonging the indecision about spent-fuel management policy and potentially complicating new reactor licensing, continued on-site storage does nothing to facilitate growth in nuclear power and might have a negative impact by complicating the ability to license new reactors.

Distinguishing the Strategies

The selection of policy alternatives ultimately depends primarily on societal preferences about the disposition of spent fuel, the growth of nuclear power, and intergenerational trade-offs. This analysis highlights the implications of each strategy in the context of these societal preferences. The findings do not perfectly distinguish the different strategies according to unique societal preferences—some priorities are consistent with multiple strategies, and some strategies are consistent with multiple priorities—but they help restrict the range of combinations. The association between the strategies and several possible priorities is shown in Figure S.2. Aggressively pursuing advanced fuel cycles is attractive primarily if constraints on repository capacity or uranium resources are important. Maintaining extended on-site storage is attractive only if all other options are deemed unacceptable. Proceeding with Yucca Mountain or the centralized storage–geological disposal strategies is most attractive when facilitating the growth of nuclear power and not leaving spent-fuel disposal for future generations are the top priorities; choosing between them depends on how important it is to increase confidence in decision consensus and repository performance. Choosing a strategy thus entails assessing these preferences among stakeholders: it might be difficult to achieve a consensus. It is likely that no single strategy will satisfy all stakeholders in all three dimensions that we examine. However, in bringing the multitude of technical and institutional considerations together in the form of a limited set of preferences, we hope this analysis will contribute to consensus building and help guide that decisionmaking process.

Figure S.2
Association Between Strategies and Possible Societal Priorities



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Abbreviations

DOE	U.S. Department of Energy
EEED	Environment, Energy, and Economic Development Program
EPA	Environmental Protection Agency
GAO	U.S. Government Accountability Office
GNEP	Global Nuclear Energy Partnership
GWe	gigawatt electrical
IAEA	International Atomic Energy Agency
IRG	Interagency Review Group on Nuclear Waste Management
ISE	RAND Infrastructure, Safety, and Environment
kgHM	kilogram of heavy metal
MIT	Massachusetts Institute of Technology
MOX	mixed oxide
MTHM	metric ton of heavy metal
NEA	Organisation for Economic Co-Operation and Development Nuclear Energy Agency
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
NWTRB	U.S. Nuclear Waste Technical Review Board
O&M	operations and maintenance
U-235	uranium-235
WIPP	Waste Isolation Pilot Plant

CHAPTER ONE

Where We Are Now, How We Got Here, and the Decisions We Face

Nuclear power is a readily available method for generating electricity that emits far fewer greenhouse gases than power generated using coal or natural gas. As such, increasing the fraction of nuclear power in the mix of energy-generation technologies is one approach to reducing emissions of greenhouse gases. Motivated by this benefit, some analysts have examined the policy and technical implications of greatly increasing worldwide nuclear generating capacity (MIT, 2003, 2010).

Although nuclear power provides about 20 percent of electricity generated in the United States (NEA, 2009b), no new nuclear generating capacity has been ordered in the United States since the River Bend Nuclear Power Plant began construction in 1977 (EIA, 2009). If new nuclear power plants are to be built in the United States, several concerns—including management of spent fuel, cost, safety, and security—will need to be overcome (DOE, 2010c; Holt, 2009b; MIT, 2003). While all of these concerns are important, the decades-long impasse over spent-fuel management perhaps looms largest as an impediment to maintaining or increasing nuclear power in the United States.

The Current Situation

Until late 2009, the national strategy for managing spent nuclear fuel was essentially that envisioned in the Nuclear Waste Policy Act of 1982 (NWPA), as amended.[1] Spent nuclear fuel (consisting of solid fuel-rod assemblies removed from nuclear power reactors) was to cool in water pools at private or municipally owned nuclear power plants and then be packaged for shipment to a federally owned and operated permanent repository located deep underground (a permanent geological repository). When the repository became available, the federal government was to be able to take title of the spent fuel and transport the fuel to the repository. According to the NWPA, the repository was required to be available to begin accepting spent fuel by 1998. The repository would isolate the spent fuel from the accessible environment until it no longer posed a

[1] Pub. L. 97-425, Pub. L. 100-202, and Pub. L. 100-203.

safety or health risk to people or biota (generally considered to be at least several tens of thousands of years).

To date, all commercial spent fuel remains at nuclear power plants, and a permanent geological repository has not been licensed. Commercial nuclear power generation in the United States currently generates about 2,000 metric tons of heavy metal (MTHM[2]) of spent fuel each year (DOE, 2008d). As of December 2008, about 60,000 MTHM were stored at current or former nuclear power plant sites nationwide (McCullum, 2009; NRC, 2010b). The 1987 amendments to the NWPA specified that Yucca Mountain, Nevada, would be the only site considered for a repository. However, after more than 20 years of research, technical investigation, and political debate, the repository has not been approved or licensed for development by the Nuclear Regulatory Commission (NRC). The Obama administration recently eliminated funding for the Yucca Mountain program (Behr, 2009), and, on March 3, 2010, the U.S. Department of Energy (DOE) withdrew its license application with NRC for Yucca Mountain to become a permanent repository for spent nuclear fuel (DOE, 2010b).

In halting the previously set course for management of spent nuclear fuel, the administration has put the current national policy on pause and embarked on a reconsideration of alternative strategies for moving forward. On January 29, 2010, the U.S. Secretary of Energy established the Blue Ribbon Commission on America's Nuclear Future to provide recommendations for managing spent nuclear fuel and other nuclear wastes. The scope of the commission entails

> a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel, high-level waste,[3] and materials derived from nuclear activities. (DOE, 2010a, p. 1)

While this pause certainly does not render irrelevant the knowledge and experience gained during the investigation of a repository at the Yucca Mountain site and might not even necessarily mean permanently abandoning Yucca Mountain, it nonetheless does represent an admission that the earlier strategy might not reach resolution and that a major policy review was warranted.

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[2] The measure MTHM includes the weight of the uranium and plutonium, as pure elements, in the spent fuel. Other chemical constituents in the fuel rods and the structural materials in the fuel-rod assemblies are not included in this measure.

[3] High-level waste is the highly radioactive by-product of reprocessing spent nuclear fuel.

Historical Background

Since nuclear power began to be used commercially for generating electricity in the United States, spent nuclear fuel has been stored at nuclear power plants. On-site storage, however, was never intended as a permanent solution for spent-fuel management. Prior to the late 1970s, the industry and U.S. government regulators intended for spent fuel to be reprocessed. Spent fuel was to be stored at commercial nuclear power plants for only a few years. This would allow radiation levels to decrease so that the spent fuel could be packaged and shipped to a reprocessing plant. At the reprocessing plant, the uranium and plutonium would be chemically separated from the relatively small amount of highly radioactive fission products. The highly radioactive fission products, as well as heavy metals that could not be recycled, would ultimately need to be disposed of in permanent storage facilities, but much of the uranium and plutonium could be reused as fuel. But because natural uranium stayed relatively inexpensive and reprocessing costs were high, the economic outlook for commercial reprocessing plants dimmed during the late 1970s. At the same time, concerns that plutonium from civilian spent fuel could be used for nuclear weapons contributed to ending federal support for commercial reprocessing (J. Carter, 1977).

After the U.S. government withdrew support for commercial reprocessing and private firms deemed it too expensive, the nation undertook a comprehensive policy review to establish a strategy for long-term management of nuclear waste. Although the likely need for a permanent geological repository had long been understood and investigations of possible repository sites and designs had begun, a realization was emerging that the technical and political challenges of spent–nuclear fuel management had been underappreciated and that a more concerted effort was required to develop a workable solution. A major step in this review was the assembly of the Interagency Review Group on Nuclear Waste Management (IRG), which involved 14 separate federal government entities (IRG, 1979). Under conditions in some ways similar to the situation we face today, the IRG sought to "develop a national nuclear waste management policy and integration program" (IRG, 1979, p. 1).

The IRG findings and recommendations laid out several of the main pillars of reasoning that led to the strategy outlined in the 1982 Nuclear Waste Policy Act. These included the arguments that the generation that benefited from the activities that produce nuclear waste should bear the burdens of disposing of it; that candidate technologies for disposal of spent fuel other than permanent geological repositories were too immature to warrant consideration for policy development and that near-term activities should be predicated on the assumption that final disposal will ultimately be in permanent geological repositories; that investigation of multiple sites within different geological environments needs to be undertaken to identify the most promising candidates; and that centralized interim storage facilities were an attractive option but are not viewed as necessary (IRG, 1979). The IRG report also assessed many of the technical details, constraints, and uncertainties and highlighted institutional and management issues that further guided policy and implementation.

With the adoption of the Nuclear Waste Policy Act in 1982, the U.S. government policy shifted de facto to support for directly disposing of spent fuel removed from reactors. The act was agnostic as to the preferred fuel cycle but did direct DOE to provide repositories for both spent fuel and high-level waste. The act required DOE to be capable of accepting commercial spent fuel by January 1998 for eventual emplacement in an underground repository. The act, however, did not mandate that owners turn over the spent fuel immediately after a repository opened or that DOE emplace the waste by a certain time.

To fund the program, utilities were required to pay a fee of one mill ($0.001) per kilowatt-hour for all electricity generated by nuclear power, which is to be adjusted as necessary to ensure the recovery of the full costs of managing and disposing of the associated waste; the fees were deposited in a Treasury account called the Nuclear Waste Fund. The DOE Office of Civilian Radioactive Waste Management was established to run the program.

In 1986, DOE selected three sites as candidates for the first repository and indefinitely deferred the mandated search for a site for a second repository. In 1987, Congress amended the NWPA by stipulating that Yucca Mountain be the sole site to be studied for suitability as a repository. Since before that time, efforts to develop the site have been continuously delayed by environmental regulatory concerns and sustained resistance from the state of Nevada.[4]

The NWPA also allowed for the federal government to develop an interim storage facility, which would be a less technically and politically involved undertaking that would allow the federal government to honor its commitment to take title to the spent fuel by the 1998 deadline while waiting for the completion of a permanent geological repository. DOE tried on several occasions in the 1980s to include an interim storage facility in its plans but was thwarted by Congress: The 1987 NWPA amendments so restricted the terms for interim storage as to effectively eliminate the option. The situation reversed itself in the 1990s when Congress tried to establish a storage facility in Nevada but was opposed by the Clinton administration (Cotton, 2010). But perhaps a more fundamental difficulty in pursuing centralized interim storage is that no state has been willing to host such a facility.

Dissatisfaction with the Yucca Mountain alternative led the Obama administration to suspend the pursuit of the program and licensing process and to once again undertake a thorough examination of technical and policy options to help inform the development of a renewed spent–nuclear fuel management strategy. Similar difficulties

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[4] Opposition within Nevada has not been universal. For a sense of the complexity of views emanating from the state, see Blue Ribbon Commission (2010).

in siting repositories have led several other countries, including Canada, the United Kingdom, and France, to undertake broadly analogous policy reviews in recent years.

Confronting the Problem Anew

If nuclear power is to be sustainable and accepted by the public, the nuclear industry and the government will need to find and agree upon a path forward to managing spent nuclear fuel that convincingly meets safety and environmental standards. Management of spent nuclear fuel has proven to be immensely challenging, both technically and politically, but one question the nation faces today is clear and essentially unchanged from decades ago: What are the alternatives for safely managing, storing, and disposing of spent nuclear fuel, and how can they be characterized in a way that provides a better understanding of the trade-offs and policy implications of the alternatives?

Some aspects of the spent-fuel management problem have not changed. Chief among these is the need for a permanent geological repository. Since geological disposal was first examined by the National Academy of Sciences in 1957 (National Research Council, 1957), subsequent research has led to a broad international consensus that, in the long run, radioactive wastes from nuclear power generation need to be disposed of in a way that does not require ongoing management and that permanent geological disposal is thus far the only technically feasible way to accomplish this (IAEA, 2003; National Research Council, 1996, 2001). For nuclear power to remain a viable long-term source of electricity, an effective system of permanent geological disposal will, at some point, be essential.

Permanent geological disposal does not need to occur immediately, however. The experience thus far of the current practice of storing spent nuclear fuel on-site at nuclear power plants for several decades suggests that there is no pressing need, from a safety or security perspective, to move the waste to a permanent geological repository. NRC has sanctioned this sentiment with a "waste confidence decision" first made in 1984 and subsequently repeated in 1990 and currently being updated again (NRC, 1984, 1990, 2008b). Experience with spent–nuclear fuel management worldwide has revealed several options for managing spent nuclear fuel prior to permanent geological disposal. Given the difficulties encountered in developing a permanent geological repository, these temporary options continue to generate interest.

Other technical, economic, and environmental issues relevant to spent-fuel management have evolved since the 1970s. One very important change is the vastly increased awareness of the negative effects of global climate change and the importance of reducing fossil fuel emissions. This awareness has prompted a renewed examination of increasing the role of nuclear power. It has also lessened environmental groups' opposition to nuclear power and begun to increase public acceptance of nuclear power.

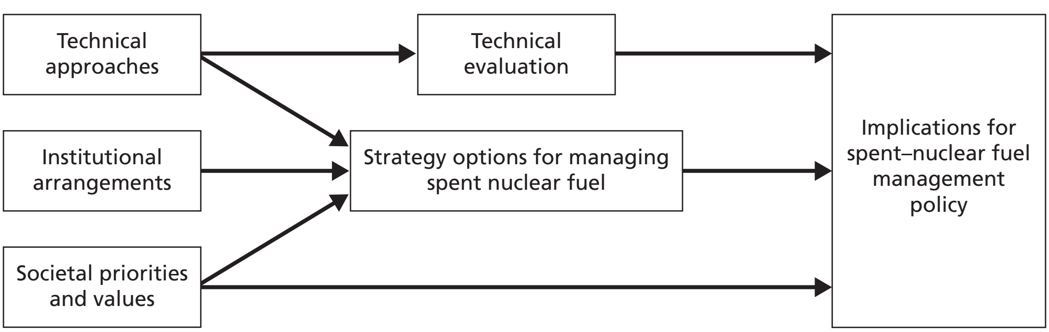
Another important difference is that deployment of nuclear power has stagnated and is far below early projections (U.S. Atomic Energy Commission, 1972). As discussed in more detail later in this monograph, this is due, at least in part, to the continued delay in the federal government taking title of the spent fuel. At the same time, because the cumulative amount of spent fuel generated is much smaller than it would have been with greater nuclear deployment, it might have led to less of a sense of urgency to resolve spent-fuel disposal than what was anticipated in the 1970s. In addition, although technologies for nuclear power generation have not changed radically, new advanced reactor designs and fuel-recycling approaches are under development. While these issues continue to be monitored and discussed, spent-fuel management policy has not substantially been updated in light of their implications. Development of a new spent-fuel management policy will need to be conducted in the context of these differences from and similarities to the past.

Objectives and Approach of This Monograph

The objective of this monograph is to review the current status of the main technical and institutional elements of spent–nuclear fuel management and to identify the implications for the development of spent-fuel management policy. We examine policy implications in the context of a range of possible strategic approaches. While the strategies considered span much of the range of options currently being considered, we do not comprehensively evaluate all policy options or attempt to recommend a particular policy approach. It is important to also note that our study looked only at waste-management issues associated with commercial spent fuel and did not address issues associated with spent nuclear fuel from defense operations.

The approach we follow in our analysis is summarized in Figure 1.1. Analysis of the key technical steps and institutional arrangements associated with spent–nuclear

Figure 1.1
Summary of Analytical Approach



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fuel management, along with consideration of societal preferences, leads to a set of strategy options. The strategy options are then compared in the context of the technical evaluation and societal preferences to elucidate implications for spent–nuclear fuel management policy.

We examine four technical options for managing spent nuclear fuel from commercial nuclear power plants:

- surface storage technologies at existing nuclear plant sites (known as on-site storage)
- centralized interim storage away from power plant sites
- advanced fuel cycles with spent-fuel recycling
- permanent disposal in a deep geological repository.

These options comprise the essential elements of any long-term strategy for spent–nuclear fuel management (Holt, 2009a). Any strategy for managing spent nuclear fuel will be built around some combination of these options. We evaluate these options in the context of five criteria:

- safety
- security
- technical obstacles
- public acceptance
- cost.

These criteria cover the key concerns about nuclear power voiced in public debates and the literature (e.g., National Research Council, 2001; Holt, 2009a; MIT, 2003).

We also review existing institutional, statutory, and regulatory arrangements related to spent–nuclear fuel management for insights about whether there are or would be barriers to implementing the technical options. We assess relevant legislation and agency roles and relationships and highlight important shortcomings and needs for improvement.

Based on the technological and institutional assessment, we construct four policy strategies that could be pursued. For each strategy, we describe its relevant characteristics, discuss the conditions that would need to prevail in order for that alternative to be favored, highlight institutional changes that would facilitate its success, and discuss implications for the future of nuclear power in the United States and the implications for future generations. The insights developed through this analysis are intended to help inform efforts to recraft the nation's strategic plan for the management of spent nuclear fuel and the future of nuclear power in the United States.

CHAPTER TWO

Technical Approaches to Spent–Nuclear Fuel Management

We examine four different approaches for managing spent nuclear fuel: on-site storage, centralized interim storage, advanced fuel cycles, and permanent geological disposal. We evaluate each approach according to five criteria: safety, security, technical obstacles, public acceptance, and cost. Our evaluation focuses primarily on the near-term implications of each approach in isolation, but it is important to note that different combinations of approaches have the potential to generate different sets of costs and benefits for the current and future generations. We assess the relative implications for the current and future generations in the final chapter.

Much has been written about nuclear waste disposal in the scientific, policy, government, environmental, and trade literatures. We reviewed these bodies of literature to determine the effects of different waste-management options according to our key criteria, as well as other metrics. We supplemented this review with extended interviews with several subject-matter experts.

On-Site Storage

Spent nuclear fuel removed from a nuclear reactor is highly radioactive, releasing very substantial amounts of energy. Spent fuel-rod assemblies must therefore be temporarily stored until they are cool enough for handling and transport. All fuel taken from a reactor is initially stored in pools where it cools both thermally and radioactively. As storage durations have increased and space in cooling pools has filled, spent fuel has begun to be transferred to dry-cask storage systems.

Spent-Fuel Pools

Spent fuel rods are initially stored in pools under at least 20 feet of water. The pools are fitted with stainless steel and aluminum racks that hold the fuel assemblies and are lined with stainless steel to prevent leaking. The reactor is connected to the pools by canals. The spent fuel is transported to the pools through these canals so as to shield workers from radiation. About one-fourth to one-third of the total fuel load is spent and removed from the reactor every 12 to 18 months and replaced with fresh fuel

(Bodansky, 1996). Because nearly all of the United States' nuclear power plants were designed when U.S. policy called for spent fuel to be sent to reprocessing plants, most nuclear power plants were designed to have relatively small pools that were to be used for short-term (i.e., ten to 15 years) storage.

In the early 1980s, when it became apparent that permanent storage would not become available any time soon, utilities began looking at options for increasing on-site spent-fuel storage capacity. Current regulations permit reracking (placing fuel-rod assemblies closer together in spent-fuel pools) and fuel-rod consolidation, subject to NRC review and approval, to increase the amount of spent fuel that can be stored in on-site pools. These approaches can quadruple the storage capacity of a pool. However, both of these methods are constrained by the size of the pools. As of 2001, spent-fuel cooling pools were more than 50-percent full at more than half of U.S. nuclear reactor sites (Macfarlane, 2001).

Dry-Cask Storage

Despite steps to increase the capacity of storage pools by reracking and consolidating fuel rods, additions to storage capacity were limited. Utilities began looking at options, such as dry-cask storage, for increasing on-site spent-fuel storage capacity. In 1985, the first dry-cask storage system was licensed under a dry-storage demonstration program in the NWPA. Now, at nuclear power plants where available pool capacity is limited or at a site that is being decommissioned, most licensees have already moved toward use of aboveground dry-storage casks.

Dry-cask storage allows spent fuel that has already been cooled in the spent-fuel pool to be surrounded by inert gas inside a container called a cask. The casks are typically steel cylinders that are either welded or bolted closed. With some designs, the steel cylinders containing the fuel are placed vertically in a concrete vault; other designs orient the cylinders horizontally. The steel cylinder provides leak-tight containment of the spent fuel. Each cylinder is surrounded by additional steel, concrete, or other material to provide radiation shielding to workers and the public. This additional material serves as a barrier preventing physical damage that might result in a release of radiation. Some of the cask designs can be used for both storage and transportation.

The amount of time that spent fuel must remain in pools before it can be transferred to dry storage depends on a variety of factors, including the initial percentage of uranium-235 (U-235) in the enriched fuel, how much of the U-235 has fissioned (fuel burnup), and the operating history of the fuel (Macfarlane, 2001). Most casks are licensed to store spent fuel that has cooled a minimum of between five and ten years in pools, depending on the cask design (IAEA, 1999).

Civilian stockpiles of spent nuclear fuel totaled more than 60,000 MTHM as of the end of 2008. This stockpile is spread over 131 civilian nuclear reactors at 65 operating nuclear power plants and nine decommissioned power plants (McCullum, 2009; NRC, 2010b). These sites are dispersed over 39 states. About 47,000 MTHM (79 percent) is stored in cooling pools; the rest is in dry-cask storage (see Table 2.1). Nine of the dry-cask storage sites are at locations without operating reactors. By 2020, it is anticipated, nearly all of the current reactor sites will have implemented dry-cask storage and roughly 30,000 MTHM will be in dry storage (McCullum, 2009).

Evaluation of Extended Reliance on On-Site Storage

On-site storage will continue to be the primary means of storing spent nuclear fuel for at least several decades. Until an alternative spent-fuel management strategy is developed, leaving spent nuclear fuel on-site will remain de facto U.S. government policy. In this case, reliance on on-site dry-cask storage will increase due to the limited storage space in cooling pools.

Safety. NRC considers dry storage safer than pool storage and has concluded that dry storage of spent fuel at nuclear power plants is safe for at least 100 years. (NRC, 1990, 2008b). Dry-cask storage systems are designed to resist floods, tornadoes, projectiles, temperature extremes, and other unusual threats to the integrity of the storage container. Over the past 20 years, there have been no identified radiation releases from spent-fuel storage that have affected the public (NRC, 2005). Environmental and other groups have argued that continued reliance on on-site storage eliminates the near-term risks of transporting highly radioactive spent fuel to a central storage facility (Holt, 1998). By allowing the fuel to cool for a longer period of time on site, it will be safer to handle and transport once it is removed from the site (GAO, 2009).

While no major incidents with on-site storage have occurred in the United States, dry-cask storage systems have had some problems. The coatings on dry-cask storage units at the Trojan reactor site in Oregon, Michigan's Palisades reactor, and Wisconsin's Point Beach reactors were found to generate hydrogen, which can cause an explosion. NRC has attributed these problems to poor cask-vendor oversight of subcontractors and failure of vendors to perform quality assessment during the design process and lack of compliance with regulatory requirements during cask fabrication (Macfarlane, 2001).

Security. NRC regulation (2004) requires that all on-site storage facilities include two barriers, constant monitoring, and an identification and lock system. To date, no nuclear power plant has been sabotaged or experienced the theft of spent nuclear

Table 2.1
Summary of On-Site Storage Situation, as of December 2008

Commercial Spent–Nuclear Fuel Storage Technique	Amount of Spent Nuclear Fuel in Storage (MTHM)
Pool storage	47,465
Cask storage	12,594
Total	60,059

SOURCE: McCullum (2009).

fuel. Nevertheless, the Union of Concerned Scientists (undated), among others, has questioned how secure nuclear waste left on site is. Some questioners suggest that, by centralizing storage, spent nuclear fuel will be more secure than it currently is (see, for instance, L. Carter and Pigford, 1999). However, as noted by Macfarlane (2001), even with a move toward off-site storage, some spent nuclear fuel will always be located at active nuclear power plants. Furthermore, the plutonium in spent nuclear fuel is encased in highly radioactive assemblies that are difficult to steal (Bunn, Holdren, et al., 2001). Recovering plutonium from these assemblies requires highly specialized equipment and training. As a result, the proliferation risks of aboveground spent–nuclear fuel storage options are likely to be low.

Technical Obstacles. Unlike the other options assessed here, the short-term technical issues associated with continued reliance on on-site storage have largely been addressed. However, many experts believe that waste stored in dry casks will eventually have to be repackaged (GAO, 2009).[1] While there are technical uncertainties regarding repackaging (e.g., whether the inner canister must be replaced), there appear to be no serious technical barriers to developing and implementing protocols for safe and secure repackaging. Nevertheless, repackaging requirements could impose additional costs and increase worker exposure to radiation, which should be considered when deciding how long it is prudent to leave spent nuclear fuel at reactor sites. This is particularly a concern for "stranded fuel"—that is, fuel stored at sites that no longer have reactors or fuel-handling equipment.

Public Acceptance. While the status quo policy has been to leave spent nuclear fuel on site, the public does not generally consider this practice acceptable. Communities located near nuclear power plants, particularly those sites that have been decommissioned and therefore no longer generate electricity, have voiced opposition to the current practice of allowing the buildup of spent nuclear fuel at such sites (NEA, 2003). As the number of decommissioned sites grows, opposition to current practices is also likely to grow and broader support for centralized storage options is likely to increase.

While issues of public acceptance have more-limited implications for existing nuclear power plants, they have created major political obstacles for the expansion of the nuclear power industry. In particular, opposition to spent-fuel storage site renewals and reactor license extensions are likely to intensify without the establishment of a plan for the eventual disposition of nuclear waste (GAO, 2009).

Cost. Companies providing nuclear power would prefer to start the process of moving spent fuel to a federal interim or permanent storage facility as soon as possible. These power companies are particularly concerned about incurring indefinite responsibility for maintaining on-site storage facilities, a concern that has grown with each delay in DOE's schedule for opening a permanent waste repository (Holt, 1998).

[1] While storage-cask renewals last up to 40 years, transportation-cask certifications currently last only five years. As a consequence, casks might need to be repackaged to meet future transportation requirements.

Should a move to longer-term reliance on on-site storage systems occur, it is unclear how these costs would be financed for new reactors that do not now have contracts with DOE for acceptance of their fuel. For currently operating nuclear power plants, it seems likely that the federal government and, ultimately, ratepayers or taxpayers will incur these costs in light of DOE's obligation to receive spent nuclear fuel.[2]

Published estimates of up-front capital costs of constructing a dry-cask storage facility range from $15 million to $30 million per site in 2009 dollars.[3] Operations and maintenance (O&M) costs vary considerably between operating and decommissioned reactors. Estimates of O&M costs for operating reactors are on the order of $1 million per year, while decommissioned reactors are expected to face annual O&M costs in the range of $4 million to $15 million in 2009 dollars.[4] In addition to these costs, there are one-time storage-system and loading costs that will vary over time as dry waste accumulates and include the cost of the storage casks, labor, and decommissioning, but these costs might be unavoidable under any options, in that they must be incurred to transfer the waste off site.

To assess the total costs of continued reliance on on-site storage, one must track the costs over time and put them in present value terms. GAO (2009) has provided the most comprehensive evaluation of the long-term cost of different storage alternatives. According to its estimates, the present value (in 2009 dollars) of on-site storage of 153,000 metric tons at the end of 100 years ranges between $13 billion and $34 billion.[5]

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2 It has been estimated that, if DOE fails to take custody of the waste in accordance with its contracts with the reactor operators, the government will continue to accumulate up to $500 million per year beyond the estimated $12 billion in liabilities that will have already accrued up to that point (GAO, 2009; Holt, 2010). This liability could be significantly affected by pending litigation, as well as legislative actions by Congress to amend the NWPA (GAO, 2009).

3 Macfarlane (2001) has estimated that the up-front capital costs for constructing a dry-storage facility are approximately $9 million per site in 1998 dollars, or approximately $15.4 million per site in 2009 dollars if inflated using a broad measure of inflation in the electric utility sector. GAO (2009) suggests that the costs would be higher, averaging around $30 million per reactor site in 2009 dollars. Many existing reactors have already incurred these costs in order to accommodate on-site dry-cask storage.

4 For operating reactors, the O&M costs are estimated at between $470,000 and $750,000 annually per site in 1998 dollars, or between $800,000 and $1.3 million per site in 2009 dollars. For decommissioned reactors, the O&M costs grow to between $4 million and $9 million annually per site in 1998 dollars (Macfarlane, 2001), or between $7 million and $15 million annually per site in 2009 dollars. Based on interviews conducted more recently with experts in the industry, GAO (2009) suggests that continued storage of nuclear waste at decommissioned sites could cost power companies between $4 million and $8 million per year.

5 The U.S. Government Accountability Office (GAO) used Monte Carlo simulation to obtain the range of cost estimates. Many of the key assumptions, including discount rates used over different future time periods and cost assumptions, were allowed to vary according to predefined distributions. For a discussion of these assumptions, see Appendix IV of GAO (2009).

Centralized Interim Storage

Centralized interim storage has been proposed as a near-term solution for addressing issues associated with the buildup of spent fuel at nuclear power plants, particularly those that have been decommissioned. Under most proposals, spent fuel would be stored in dry casks, similar to the way in which dry-cask storage works at nuclear power plants, although the spent fuel from many reactors would be consolidated at a single site after it has had an opportunity to cool sufficiently. Operating reactors would be able to reduce the volume of spent-fuel rods that are kept in pools and would no longer need to build dry-storage capacity on site. If owned by the federal government, centralized storage facilities would allow DOE to fulfill its obligation to take custody of spent fuel from the nuclear power plant operators.[6] In so doing, the federal government would reduce its total liability to the industry, potentially saving taxpayers billions of dollars in payments to the owners of nuclear generating plants.

Proposals to develop centralized interim storage facilities have been made at various times over the past few decades. The Office of the Nuclear Waste Negotiator attempted to identify a community to host an interim storage facility following the 1987 amendment to the NWPA. Over the years, a number of Native American tribes have expressed interest in hosting an interim storage site, although no proposals have been successfully implemented thus far, largely due to opposition from neighboring states.

DOE estimates that, if statutory, regulatory, siting, construction, and financial issues were resolved expeditiously, a centralized facility to accept nuclear waste could begin operating as early as six years after construction began. Many experts, however, believe that the process from site selection until the facility opens is likely to take between 17 and 33 years (GAO, 2009). The effective life of an interim storage facility could be 100 years or more (Bunn, Holdren, et al., 2001).

Evaluation of Centralized Interim Storage

Centralized interim storage does not eliminate the need for developing a long-term disposal option, but it might provide other benefits. We discuss the potential positive and negative aspects of moving to centralized interim storage in this section, drawing heavily from a study conducted by the Nuclear Energy Study Group of the American Physical Society (2007), which provides an in-depth analysis of issues related to interim storage development.

Safety. If storage of spent fuel is centralized at particular locations, safety benefits might accrue as infrastructure and procedures are enhanced to guard the much-larger volumes of waste than would be typically stored on site. Analysis of these safety benefits suggests that they are likely to be small. For instance, the Nuclear Energy Study

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6 Alternatively, DOE could meet its obligations by leasing space in a private facility.

Group of the American Physical Society (2007, p. i) found that "[t]here are no substantive safety or security reasons for establishing consolidated interim storage." This is because the same storage technologies are employed both on and off site and the operational, maintenance, and security requirements are the same for centralized storage as they are for on-site storage.

Centralized interim storage generally requires two separate movements of nuclear fuel: from the power plant to the interim storage site and, ultimately, from the interim storage site to the site for permanent geological disposal. The only exception would be the case in which the interim storage facility is collocated with a geological storage site. In comparing centralized interim storage with other nuclear waste–management options, questions of safety depend primarily on the extent to which this additional transportation requirement poses additional radiological risks. Analysis of the potential risks, as well as the national and international experience with spent-fuel transport, led the National Research Council (2006, p. 7) to find that

> transport by highway (for [tens of tons]) and rail (for [hundreds to thousands of tons]) is, from a technical viewpoint, a low-radiological risk activity with manageable safety, health, and environmental consequences when conducted in strict adherence to existing regulations.[7]

Similar conclusions have been made in numerous other studies, as noted by the Nuclear Energy Study Group of the American Physical Society (2007).

Security. Of those studies that do provide analysis of the security issues associated with a move to interim storage, most suggest that the risks are likely to be quite small and stem primarily from threats encountered during the transportation of the spent fuel. The transportation risks have not been well defined or analyzed in unclassified studies.[8]

Technical Obstacles. Centralized interim storage is technically feasible using dry casks already in use. Techniques for shipping spent nuclear fuel and high-level radioactive waste have already been employed, although only in a limited number of instances in the United States. Consequently, there appear to be no appreciable technical barriers

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[7] The original defines amounts in a footnote:

> This report identifies two general types of transportation programs, small-quantity shipping programs and large-quantity shipping programs. While there is no precise quantity demarcation between these two program types, the former involve the shipment on the order of tens of metric tons of spent fuel or high-level waste, while the latter involve the shipment on the order of hundreds to thousands of metric tons.

[8] The National Academy of Sciences has stated,

> Malevolent acts against spent fuel and high-level waste shipments are a major technical and societal concern, but the committee was unable to perform an in-depth examination of transportation security because of information constraints. The committee recommends that an independent examination of the security of spent fuel and high level waste transportation be carried out prior to the commencement of large-quantity shipments to a Federal repository or to interim storage. (National Research Council, 2006, p. 3)

to establishing and operating one or more centralized interim storage facilities. Should spent fuel stored in casks need to be repackaged in the future, having large quantities at a single location might provide technical advantages tied to economies of scale.

Public Acceptance. While centralized interim storage is technically straightforward, it faces a number of hurdles stemming from issues associated with public acceptance. The history of attempts to establish nuclear waste storage or disposal sites, including those designed to accept low-level wastes, clearly shows that host-state and host-community acceptance requires that local and regional benefits, such as employment opportunities, transportation upgrades, and direct benefits, outweigh perceived environmental costs and safety risks that might lower property values. To date, a few American Indian tribes have accepted proposals to host interim storage sites, although opposition from other agencies or affected groups has impeded these proposals.[9] Some of these concerns stem from fear that the proposed interim storage facility might, in fact, become permanent, or at least be utilized for much longer than originally anticipated. Other concerns stem from perceived safety issues associated with transporting and storing spent nuclear fuel.

Cost. The consolidation of waste might allow the decommissioning of sites that have already been shut down, which could provide some cost savings to nuclear plant owners and free up land for other purposes. If a large number of the existing nuclear power plants are abandoned over the next 50 years, moving to a centralized storage facility might appreciably reduce overall security and maintenance costs. Offsetting this savings would be the additional costs for developing the centralized facilities and transporting spent fuel to them. Considering both the savings and the costs, it is not clear that centralized interim storage offers a cost advantage over long-term reliance on on-site storage. A recent estimate of the cost of implementing centralized storage for 100 years is in the same range as the costs of on-site storage (GAO, 2009).

Advanced Fuel Cycles

The nuclear fuel cycle is the series of activities involved in the production, utilization, and disposition of fuel for nuclear power generation. Because the choice of fuel cycle influences the waste streams from nuclear power generation, it is a central consideration in addressing questions about nuclear-waste disposal. However, because the fuel cycle also has important implications for primary fuel resource management, reactor design, safety, and security, it is difficult to examine the nuclear fuel cycle in the context of spent-fuel management alone.

[9] For example, the Skull Valley Band of the Goshute Indians proposed to locate a private fuel storage facility on its reservation in Utah, but the state opposed the licensing and construction of the facility and the Department of Interior denied approval of land transfers needed for the construction and operation of the facility.

There are many possible configurations of the nuclear fuel cycle. In the simplest cycle, fresh fuel is fabricated from enriched natural uranium, burned in a thermal reactor until it is no longer an effective energy source, and then directly disposed of. This is referred to as an open or once-through cycle because none of the fuel is recycled, despite the fact that the spent fuel contains substantial energy potential. This is the cycle currently employed in all commercial reactors in the United States. At the other extreme, repeated recycling of spent fuel can, in principle, be used in such a way that all of the initial uranium and elements heavier than uranium (together called actinide elements) produced in the reactor are consumed. This type of cycle is referred to as fully closed because all of the energy potential of the initial fuel is consumed (NEA, 2006). A fully closed cycle still produces waste fission products that must be disposed of as high-level waste. A closed fuel cycle is substantially more complicated than an open cycle because it requires technically advanced reactor designs to consume the actinides and potentially complex chemical-partitioning methods to separate the different components of the spent fuel. Considerable additional research and development are required before the technical, environmental, and commercial feasibility of a fully closed cycle can be determined.

Between these two ends lie any number of possible intermediate configurations. In one intermediate configuration, spent fuel from a thermal reactor is partitioned to recover the plutonium produced during reaction. The plutonium is then blended with natural or depleted uranium[10] to produce a mixed-oxide (MOX) fuel that is recycled into thermal reactors. Because of the high radiation and heat content of spent MOX fuel, as well as the cumulative production of undesirable uranium and plutonium isotopes, only one round of recycling is feasible with this approach (IAEA, 2005), giving rise to the name single recycle. The spent MOX fuel, as well as the fission products and residual uranium separated from the original spent fuel, must be disposed of or stockpiled.

Single recycle is the method used in conventional spent-fuel reprocessing and has been in commercial operation in civilian nuclear power reactors for more than 50 years. France, the United Kingdom, Russia, Japan, and India currently operate facilities that reprocess spent fuel for the purpose of producing MOX fuel. In some cases, they provide contract reprocessing for other countries (IAEA, 2005). No system more advanced than single recycle has reached commercial operation (IAEA, 2005).

Despite early commercialization of single-recycle systems, several countries, including the United States, have adopted as policy a once-through fuel cycle. The fraction of spent fuel that is reprocessed and recycled as MOX fuel is quite small: More than 90 percent of the electricity generated by nuclear power worldwide is generated

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[10] Natural uranium ore contains 0.711 percent U-235. To produce a reactor fuel, the U-235 concentration is enriched to between 3 and 5 percent. The tailings from the enrichment process are referred to as depleted uranium and contain roughly 0.3 percent U-235 (MIT, 2003).

at plants utilizing a once-through fuel cycle (MIT, 2003). The reasons recycling is not more common are varied. Spent-fuel reprocessing and recycling affect many aspects of the nuclear fuel cycle, and there are both potential benefits and drawbacks to reprocessing. As experience has been gained and circumstances have changed, the relative weights of these benefits and drawbacks have evolved with time. Three of the most-important issues related to spent-fuel reprocessing are supplies of uranium, nuclear-weapon proliferation, and management of waste.

Uranium Resources

The principal reason for reprocessing spent nuclear fuel is to recover plutonium produced during reaction to recycle into new fuel. As commercial nuclear energy first emerged in the 1950s, recycling of spent nuclear fuel in fast reactors was viewed as the standard strategy (IAEA, 2005). Projections called for rapid growth of nuclear power in the United States, reaching 1,000 gigawatts electrical (GWe) by 2000 (U.S. Atomic Energy Commission, 1972). Fueling these reactors would require substantial amounts of uranium. In light of great uncertainty about uranium-ore resources and prices, spent-fuel recycling was viewed as essential to ensuring adequate supplies of fissile materials for reactors. In addition, reprocessing technologies were already well developed prior to the emergence of nuclear power as a result of efforts to separate plutonium for nuclear weapons during and since World War II (Jackson, 2003; IAEA, 2005). Hence, nuclear reactors and spent-fuel reprocessing were viewed as part and parcel of nuclear technology, contributing to the proclivity toward extracting fissile material from spent fuel.

However, uranium prices have remained relatively low as new sources of uranium ore continue to be discovered and exploited (Jackson, 2003; IAEA, 2005). In addition, early assumptions about the growth of nuclear power proved to be overly optimistic; as of 2008, nuclear electricity-generating capacity in the United States was just 100 GWe (NEA, 2009b), one-tenth of what had been anticipated decades earlier. Demand for uranium has therefore been much lower than was once anticipated. Consequently, conservation of uranium resources is not a convincing rationale for reprocessing spent fuel, at least at this time. A case could be made that countries lacking substantial natural uranium resources or friendly relationships with countries that possess such resources have a motivation to undertake reprocessing. The United States, however, does not fall into this category.

Proliferation Risk

A negative consequence of spent-fuel reprocessing is its potential to increase the risk of nuclear-weapon proliferation. The concern is that the separated plutonium might be diverted from the reprocessing stream to build nuclear weapons. Indeed, reprocessing technology was originally developed for exactly this purpose. Although the isotopic composition of plutonium separated from commercial spent nuclear fuel (so-called reactor-grade or power-grade plutonium) makes it inferior to weapon-grade plutonium for the purposes of nuclear weapons, it is nonetheless clear that it can still be used to make nuclear weapons (Mark, 1990; U.S. Congress Office of Technology Assessment, 1993; National Academy of Sciences, 1994). In fact, DOE conducted a successful test of a nuclear weapon made from reactor-grade plutonium in 1962 (DOE, 2010d).

Concern over nuclear-proliferation risks led the United States, in 1977, to adopt a policy to "indefinitely defer" commercial recycling of plutonium (J. Carter, 1977). The nascent commercial reprocessing industry in the United States, which suffered from poor performance and regulatory compliance problems (Jackson, 2003; Union of Concerned Scientists, 2008; Gillette, 1974), shut down; no commercial reprocessing has occurred in the United States since. Despite U.S. efforts to convince the rest of the world to follow suit, several countries continue reprocessing. Since that time, the United States has conducted extensive research into developing advanced fuel cycles for nuclear power. Other international efforts are pursuing similar goals (IAEA, 2005). One of the key design criteria of such research is that any new reprocessing methods minimize the risk of proliferation (e.g., DOE, 2010c). Although many novel technical concepts are being examined, these efforts are in the research or development stages and are expected to be so for several decades before they could become commercially available (IAEA, 2005; NEA, 2006).

Waste Management

As the difficulties of finding a permanent solution to the problem of nuclear-waste disposal mounted, interest in reprocessing began shifting away from the front end of the nuclear fuel cycle toward nuclear-waste management at the back end of the cycle. Where spent-fuel recycling was once targeted primarily from a fuel-resource conservation perspective, it is increasingly being considered for its potential to greatly reduce waste repository capacity requirements. This is by no means a foregone conclusion, however, because the amount and characteristics of advanced fuel-cycle wastes depend on technology choices and operational decisions. Further, advanced fuel cycles will have little benefit in terms of reducing long-term radiation exposure to the biosphere. These points are discussed in this section.

Exactly how fuel reprocessing and recycling would influence waste-disposal requirements depends on the details of the overall system. In general, partitioning spent fuel into separate components provides flexibility in terms of waste management because it allows the different components, having different properties and disposal requirements, to be treated separately, including being recycled into new fuel. Spent nuclear fuel consists of three general components: uranium, fission products (the primary constituent of high-level waste), and transuranic elements (mainly plutonium, but also small amounts of neptunium, americium and curium).[11] The exact proportions of these components depend on the extent of initial uranium enrichment and fuel burnup in the reactor but are typically about 95 percent uranium, 4 percent fission products, and 1 percent transuranics by weight (Bodansky, 1996; Jackson, 2003; MIT, 2003).

To illustrate how the fuel cycle influences the relative amounts of different waste components, annual material streams adapted from the Massachusetts Institute of Technology (MIT) (2003) for three representative fuel cycles are shown in Table 2.2. The fuel cycles shown include the once-through, single-recycle, and "balanced" closed fuel cycles. This particular closed fuel-cycle configuration utilizes a mix of thermal and fast burner reactors such that all the transuranic elements produced in the thermal reactors are consumed in the fast reactors.[12] This is not the "purest" closed fuel cycle in that, while all transuranic elements are consumed, a substantial amount of residual uranium remains. A pure breeding cycle consisting of only fast breeder reactors is theoretically capable of consuming all the initial uranium and produced transuranics (NEA, 2006). While this cycle would greatly reduce raw-uranium demand and leave no residual uranium, it is otherwise quite similar in terms of waste management to

Table 2.2
Sample Material Flows for Different Nuclear Fuel Cycles

Flow	Once Through	Single Recycle	Closed[a]
Inputs			
Uranium-ore feedstock (103 MTHM/yr)	102	85.7	55.3
Fresh uranium-oxide fuel (103 MTHM/yr)	9.97	8.37	5.40
Fresh MOX or fast-reactor fuel (103 MTHM/yr)[b]	0	1.59	1.56
Outputs			
Separated uranium (103 MTHM/yr)[c]	—	7.80	4.77
Spent fuel (103 MTHM/yr)	9.97	1.59	0
High-level waste (103 MTHM/yr)	0	0.44[d]	0.47[d]

SOURCE: Values from MIT (2003), adjusted for 500 GWe (five times current U.S. nuclear capacity).
[a] Balanced closed fuel cycle from MIT (2003).
[b] Produced from recycled spent fuel.
[c] Separated uranium might not require deep geological disposal.
[d] Spent-fuel recycling is accompanied by significant amounts of radioactive process waste, some of which will require deep geological disposal.

[11] The transuranic elements are sometimes divided into plutonium and the "minor actinides" (neptunium, americium, and curium).

[12] The configuration is similar to scheme 3a of NEA (2006).

the balanced closed fuel cycle (NEA, 2006). Note that the values in Table 2.2 are for producing 500 GWe, which is about five times the current U.S. nuclear generating capacity (NEA, 2009b).

The material flows in Table 2.2 illustrate several interesting points. First, as has been noted in prior studies, the single recycle uses nearly as much uranium ore as the once-through cycle (about 16 percent less). Because of its limited benefit in terms of uranium conservation, the single-recycle system has always been viewed as an interim step toward a more completely closed fuel cycle (Holt, 2008). The balanced closed fuel cycle provides a more substantial uranium-ore reduction (46 percent). As noted above, however, uranium ore remains plentiful and cheap and is not a constraining factor for nuclear power.

A second point illustrated in Table 2.2 is that the amounts of waste materials differ substantially among the fuel cycles. An important uncertainty regarding waste volumes is that the fate of uranium separated from spent fuel during reprocessing (referred to as separated uranium or reprocessed uranium) is not entirely clear. Because of contamination with undesirable uranium isotopes, minor actinides, and fission products, it is technically difficult and expensive to reenrich and recycle separated uranium into new fuel (IAEA, 2009b). Consequently, while some separated uranium has been recycled, most has been stockpiled, awaiting a time when recycling becomes cost-effective or a disposal option becomes available (IAEA, 2007a, 2009b; Davis, 2009). The United States and other countries with nuclear power have no established practices or policies regarding management of separated uranium; outside the United States, decisions are typically left to individual utilities (IAEA, 2009b). Separated uranium is much less radioactive than high-level waste or spent nuclear fuel, so, if not recycled, it could potentially be disposed of separately from these other components. One possibility is that it might be approved for shallow geological disposal, possibly returning it to the mines from which the uranium ore was originally extracted (IAEA, 2007a; NEA, 2006). More-advanced fuel cycles under consideration might be able to separate uranium at sufficient purity for it to be easily recycled or disposed of as low-level waste (DOE, 2006).

If separated uranium does not require deep geological disposal, then even the single-recycle fuel cycle substantially reduces the amount of waste needing permanent disposal in a deep geological repository (about 80 percent). The closed fuel cycle reduces waste requirements by an even greater amount (about 95 percent). However, the amount of waste reduction does not translate into an equivalent reduction in the capacity requirement of a permanent geological repository. Rather, repository size is dictated largely by the heat load generated by the emplaced waste because waste packages must be spaced sufficiently far apart to allow heat to dissipate (e.g., Chow and Jones, 1999; NEA, 2006). The inventory of highly radioactive fission products in the single-recycle and closed fuel-cycle wastes is essentially the same as that in the once-through fuel cycle (MIT, 2003). Because heat generation is initially dominated by the fission products, there is little difference between the initial heat load from bulk spent fuel (from the once-through cycle) and separated high-level waste (from the single-recycle or closed cycle) despite the much smaller volume of the latter. Consequently, for waste emplaced within about 50 years of being removed from a reactor, the single-recycle or closed cycle provides little benefit in terms of decreasing the required capacity of a permanent geological repository (NEA, 2006).

In the case of the closed fuel cycle, it would be possible to substantially reduce the thermal load on the repository by allowing the high-level waste to cool for an extended period prior to disposal. The absence of long-lived transuranic elements in closed fuel-cycle waste leads to faster cooling than that of the once-through and single-recycle fuel cycles. After a cooling period of 200 years, the heat generated by closed-cycle waste would be a factor of about 18 less than that of the once-through or single-recycle waste (NEA, 2006). This greatly reduced thermal load would allow the waste packages to be placed closer together, resulting in a much smaller repository volume.

An additional consideration relevant to waste volumes is that spent-fuel reprocessing is accompanied by significant amounts of long-lived low- and intermediate-level radioactive process wastes (e.g., chemical residues, processing equipment, protective clothing contaminated with transuranic elements),[13] which must also be disposed of in geological repositories (NEA, 2006; MIT, 2003; M. Schneider and Marignac, 2008; Davis, 2009). The volume of such waste for the single recycle and closed cycle might be greater than the volume of high-level waste (NEA, 2006).

A third important implication of the material flows in Table 2.2 is that the choice of fuel cycle influences the radioactivity level of wastes emplaced in a permanent geological repository but ultimately has little influence on the long-term safety and environmental risk of a repository. In a closed fuel cycle, all the transuranic elements are consumed in the reactor, leaving only fission products and process wastes requiring permanent deep geological disposal. Fission products are initially the most radioactive component of spent fuel, dominating the overall radioactivity profile for the first 200 years or so. After that, the overall radioactivity is dominated by the much-longer-lived transuranic elements (MIT, 2003). Eliminating transuranic elements from the waste thus substantially decreases its long-term radioactivity: After 1,000 years, the activity of the closed fuel-cycle waste will have decayed by more than a factor of 100 relative to that of the once-through or single-recycle options (NEA, 2006). This significantly reduces the hazard associated with direct contact with the waste, such as an accidental breach of a waste repository, in the far future.

The eventual safety and environmental risk of waste from a permanent geological repository is expressed as the annual effective radiation dose to an average member of the critical group affected by the repository. The dose is a complex function of the

[13] Long-lived low- and intermediate-level radioactive waste is an international waste classification that is broadly equivalent to the transuranic-waste classification used in the United States.

amounts of various radionuclides present at each point in time, repository performance, and environmental mobility of individual elements (NEA, 2006). Environmental mobility turns out to be a particularly critical factor because the relative mobility of different elements varies dramatically. In particular, transuranic elements are generally far less mobile than many fission product elements. Consequently, certain long-lived fission products contribute to the dose in far greater proportion than their contribution to overall radioactivity. For example, in most scenarios, the dose is dominated by long-lived fission products, such as iodine-129 and technetium-99, for 100,000 years or more, which is long after their activity levels have dropped far below those of long-lived transuranic elements (NEA, 2006; MIT, 2003). Thus, despite the fact that a closed fuel cycle eliminates transuranic elements from the waste and decreases the overall radioactivity by more than two orders of magnitude, the resulting decrease in dose is far less.

In summary, a closed fuel cycle can greatly reduce required permanent geological repository capacity if the high-level waste is allowed to cool sufficiently on the surface prior to emplacement in the repository. However, under most conditions, a closed fuel cycle will provide little benefit in terms of reducing the long-term human and environmental health risk posed by the disposed waste.

Evaluation of Advanced Fuel Cycles

As noted earlier, there are many possible configurations for advanced fuel cycles. Based on the preceding discussion, it is clear that the single-recycle fuel cycle provides little benefit in terms of conserving uranium ore, decreasing geological repository capacity requirements, or reducing environmental risk. In addition, it creates a proliferation risk that the United States has deemed unacceptable. It is therefore unlikely that the United States will implement the current commercial single-recycle fuel cycle. Consequently, we consider only a closed fuel cycle for the remainder of this monograph.

Spent-fuel reprocessing is the most complex step in the nuclear fuel cycle. Compared to other stages in the fuel cycle, during reprocessing, it is more difficult to monitor activities and material flows, assess vulnerabilities, and implement safeguards. In addition, experience with commercial-scale reprocessing is limited to that associated with single-recycle systems. Little is known about other reprocessing methods, fuel fabrication, and fast–breeder reactor technologies that would be required in a more fully closed fuel cycle. For these reasons, the safety, security, and other implications of more-advanced fuel cycles are highly uncertain. In some places, we draw inferences about advanced fuel cycles from experience with conventional reprocessing.

Safety. There are several potential safety concerns related to advanced fuel cycles. These include increased transportation of spent fuel and high-level waste, environmental, public, and worker safety effects of reprocessing and fuel-fabrication operations, and safety concerns with fast nuclear reactors. As noted earlier, transportation of spent nuclear fuel and high-level waste is highly regulated in the United States and has been found to be safe. In Europe, where France and the United Kingdom provide reprocessing services for several other countries, spent fuel and high-level waste have been transported extensively with a safe record.

Environmental impacts of conventional aqueous reprocessing methods include release of radioactive gases, liquids, and solids, as well as toxic, corrosive, and combustible chemicals (IAEA, 2005; Jackson, 2003; M. Schneider and Marignac, 2008). Compared to the once-through, more-advanced fuel cycles have more-complicated waste streams that produce more mobile interim and waste products, creating greater risk of short-term environmental harm. The U.S. experience with spent-fuel reprocessing is limited to the short operational life of the West Valley, N.Y., plant from 1966 to 1972. Vitrification and encasement of the high-level waste from West Valley was completed in 2002 (the high-level waste remains on site). The site is environmentally contaminated, and the cleanup is expected to take 40 years (West Valley Environmental Services and URS Corporation Washington Division, 2009; Union of Concerned Scientists, 2008). In addition, one of the many reasons the plant closed was difficulties in meeting regulatory requirements for worker radiation-exposure levels (Gillette, 1974).

Experience with the much more-mature reprocessing operations in France and the United Kingdom indicates that safety can improve considerably over time. Early environmental and worker safety records at La Hague in France and Sellafield in the United Kingdom were poor but have improved substantially in concert with improved technology and increasingly stringent regulations. At La Hague, for example, environmental and human exposures have decreased substantially over the years, even as reprocessing output has increased many-fold (IAEA, 2005; M. Schneider and Marignac, 2008).

As part of their advanced fuel-cycle research, the United States and several other countries are examining new reprocessing methods, including advanced aqueous reprocessing and pyroprocessing approaches (DOE, 2006, 2010c; IAEA, 2005; NEA, 2006). Pyroprocessing entails completely different methods, equipment, and chemical reagents, conceivably with safety implications very different from those of aqueous reprocessing.

In addition to new reprocessing methods, closed fuel cycles also require new fast-reactor designs. Worldwide experience with electricity-generating fast reactors is very limited, with only a small number of demonstration or prototype reactors. With the closure of France's Phenix in 2009, only one fast reactor, the Beloyarsky-3 in Russia, remains in operation (IAEA, 2009a). Consequently, it is difficult to derive a meaningful safety record. Monju, a liquid sodium-cooled fast reactor in Japan, shut down in 1995 before it was fully operational because of an accident involving a sodium leak (Pollack, 1996). No one was injured, and the environmental impact was insignificant. Japanese authorities attempted to cover up the incident, however, resulting in a public relations debacle that eroded public support for the nuclear enterprise in Japan (Normile, 2009).

Security. The major security concern when considering advanced fuel cycles is nuclear-proliferation risk. All existing reprocessing methods entail separating and stockpiling plutonium for at least several months before the plutonium can be used to fabricate recycled fuel. The once-through cycle, in which plutonium is never separated from the highly radioactive spent fuel, is inherently more secure. Consequently, as noted earlier, the United States has had a policy of not reprocessing spent fuel since 1977. Along with several other countries, the United States is conducting research into improved monitoring, physical safeguards, and reprocessing methods that decrease the accessibility and amount of fissile materials (DOE, 2006; 2010c). For example, the International Framework for Nuclear Energy Cooperation (IFNEC),[14] in which the United States plays an important role, is exploring a nuclear fuel services concept. The objective is to enhance the reliability and security of fuel supply and services, including spent-fuel reprocessing and recycled-fuel fabrication, by having these services provided to the world market by a limited number of trusted states (IFNEC, 2010; GAO, 2008).

Technical Obstacles. The technical challenges of developing a closed fuel cycle are imposing. Due to limitations in chemical and isotopic separation during reprocessing, repeated recycling of fuel leads to the buildup of various actinide isotopes, fission products, activation products, and other contaminants into the reactor fuel that can degrade the quality of the nuclear reaction. This is the main reason that spent MOX fuel is rarely reprocessed and recycled and that current commercial technology is limited to single-recycle operations. There are considerable challenges involved in developing an overall system in which the inputs and outputs among spent-fuel reprocessing and fast-reactor burning are appropriately matched, while, at the same time, waste production, natural resource use, cost, and proliferation risk are minimized (NEA, 2006; IAEA, 2005). Research on approaches to optimize these factors has been under way by individual countries and international consortia for many years, but most estimates indicate that a workable solution is still decades away (GAO, 1993; DOE, 2010c; Holt, 2008; NEA, 2009a; Jackson, 2003; IAEA, 2005).

Public Acceptance. Implementing a closed fuel cycle would involve new types of nuclear power infrastructure. This would require, at a minimum, one large spent-fuel reprocessing plant, new uranium-enrichment and fuel-fabrication facilities, and a new fleet of fast reactors. Given the substantial expansion in infrastructure required, issues of public acceptance could easily surpass those associated with continued surface storage or permanent geological disposal. Such concerns are likely to be amplified by the fact that the United States' limited experience with reprocessing was marked by poor performance and has left a legacy of environmental contamination. Power generation from fast reactors worldwide has been a commercial failure highlighted by technical problems, further shaping the public impression of an advanced fuel-cycle option.

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[14] IFNEC was formerly called the Global Nuclear Energy Partnership.

On the other hand, it is possible that the benefit of closed fuel cycles in terms of long-term waste management would lend some support for a closed fuel-cycle option. Given that waste disposal is an important factor in the current logjam on nuclear policy, the fact that a closed fuel cycle might reduce the amount of highly radioactive waste could help facilitate public acceptance. Such a supposition, however, remains to be tested.

Cost. Compared to the current once-through fuel cycle, transitioning to a closed fuel cycle would affect costs in several ways. Cost analyses by Bunn, Fetter, et al. (2003), E. Schneider, Deinert, and Cady (2009), Organisation for Economic Co-Operation and Development Nuclear Energy Agency (NEA) (2006), and Grubert and Patiño-Echeverri (2009) identify several important cost elements, including building and operating fast reactors; capital investments in a new generation of reprocessing, enrichment, and fuel-fabrication plants; transporting the fuel to the reprocessing plant; reprocessing the fuel; and disposal of the high-level, intermediate-level, and low-level wastes from reprocessing. Plutonium and uranium recovered from spent fuel and recycled into new fuel would reduce the cost of fuel production. Note that the costs of developing and demonstrating reprocessing plants and fast reactors needed for an advanced cycle would add a substantial amount to the total cost. None of the cost analyses attempts to estimate this.

A difficulty with estimating costs for advanced fuel cycles is that most aspects of these cycles are far from the commercial stage. Further, there is a wide variety of potential advanced fuel cycles, each of which could have very different costs. Hence, there are essentially no empirical data, and, therefore, costs are highly uncertain. Even conventional reprocessing, which has been in commercial operation for decades, has been run by a small number of state-owned firms that have been reluctant to share costs and prices publicly. Using the best available data, Bunn, Fetter, et al. (2003) estimated the value of several cost elements necessary for an advanced fast-reactor fuel cycle to be cost-competitive with the once-through cycle (a "break-even" analysis). Their results show that the costs of uranium ore, uranium enrichment, fast-reactor construction and operation, interim spent-fuel storage, spent-fuel reprocessing, or waste disposal would need to change by factors of several before an advanced fuel cycle becomes cost-competitive with the current once-through fuel cycle.[15] The result of their analysis is that an advanced fuel cycle is not close to being cost-competitive with the current

[15] At the time of that analysis, uranium prices had been below $50 per kilogram for several years and showed no signs of increasing. Since that time, uranium prices underwent a sharp increase, briefly peaking at $350 per kilogram in 2007. Prices quickly fell again and have since dropped to below $125 per kilogram and continue to fall. This price spike does not necessarily indicate any fundamental change in long-run uranium prices or availability. Historically, prices of raw ore materials have generally fallen over time, even in the face of increasing demand, as extraction technologies become more efficient (MIT, 2003). Recent large uranium resource discoveries in Saskatchewan and the western United States are expected to keep uranium prices low for many years to come. This conclusion was iterated by MIT (2010).

once-through fuel cycle. They conclude that "the margin between the cost of reprocessing and recycling and that of direct disposal is wide, and is likely to persist for many decades to come" (p. ix). An analysis by Grubert and Patiño-Echeverri (2009) came to very similar conclusions.

Permanent Geological Disposal

Each of the first three preceding technical options will ultimately need to be followed by permanent geological disposal. Permanent geological disposal refers to the emplacement of spent nuclear fuel and high-level waste in tunnels, galleries, or shafts several hundred meters underground with no intention of retrieving it in the future (IAEA, 2003). It is intended to isolate nuclear waste from the biosphere until the material is no longer harmful to human health or the environment. This is challenging because of the very long half-lives of the radionuclides in spent nuclear fuel. The most likely pathway for radionuclides to ultimately reach the biosphere is from groundwater seeping into the repository, corrosion of the waste containers, and migration of the contaminated groundwater to drinking or agricultural water systems (IAEA, 2003; NEA, 2006; MIT, 2003). A permanent geological disposal system functions based on a defense-in-depth concept consisting of physical containment, slow release, retardation of flow by geochemical processes, and dispersion and dilution in the accessible environment (IAEA, 2001; NEA, 2006). This is achieved through a combination of engineered (e.g., canisters, drip shields, buffer materials) and natural (geological and hydrologic) barriers. By the time the waste reaches the biosphere, it will have decayed sufficiently and been sufficiently diluted that it is no longer hazardous (NEA, 2006; IAEA, 2001, 2003).

The waste package is expected to maintain integrity sufficient to isolate the waste from groundwater for at least several thousand years (DOE, 2002; IAEA, 2003; NEA, 2006). While the radioactivity will have dropped substantially during this time, the radioactive hazard remains elevated for hundreds of thousands of years, long after most engineered barrier systems will have broken down (MIT, 2003; NEA, 2006). Hence, the most critical aspect of the performance of a permanent geological repository system is the characteristics of the geological formation in which the waste is emplaced. A desirable environment for permanent geological disposal is one with long-term geological stability, low groundwater content and flow, stable geochemical conditions, and suitable engineering properties (IAEA, 2003).

In detail, the concept of permanent geological disposal encompasses a wide range of variations, including different rock types (e.g., volcanic, granitic, shale, clay, salt), different repository design and emplacement methods, and different waste packaging and engineering barrier designs (National Research Council, 2001; IAEA, 2001). Each of these could have important effects on the evaluation, according to our criteria.

However, given the wide range of spent-fuel management options considered in this study and the qualitative nature of our evaluation, we consider a general permanent geological disposal model. Certain aspects, particularly costs, are based specifically on the Yucca Mountain design.

Evaluation of Permanent Geological Disposal

In assessing the implications of a permanent geological disposal alternative, such as that proposed for Yucca Mountain, we consider only the implications for the near term—meaning the next several decades over which the different alternatives we consider could be implemented. We do this so that implications of the different alternatives can be compared over approximately equal time periods. Each of the alternatives also has implications for the longer-term, beyond 50 years or so. We account for differences in these longer-term implications when we compare the societal impact of the different alternatives on current and future generations.

Safety. The greatest near-term safety risks associated with long-term geological disposal are similar to those associated with on-site or centralized interim storage: the handling of waste as it is packaged and transported. These risks are generally considered to be small, as discussed previously. Additional safety concerns for permanent geological disposal would include the risk of environmental contamination (e.g., through waste-package rupture and leakage) and worker safety during emplacement of the waste packages. None of these activities represents a particularly challenging engineering effort, however, and safety risks are anticipated to be small.

Security. Direct geological disposal of spent nuclear fuel provides the most security against proliferation of any of the alternatives considered. This approach adds to the already-secure conditions of on-site and centralized interim storage by isolating the spent-fuel packages hundreds of meters below the surface in backfilled tunnels. If nuclear waste is stored deep underground, the waste will be much more difficult to tamper with or steal.

Technical Obstacles. No significant technical obstacles to developing, loading, and closing a permanent geological repository are anticipated. The International Atomic Energy Agency (IAEA) (2003) notes that there is substantial worldwide experience with excavation and construction of self-supporting underground cavities in various rock types at several-hundred-meter depths. That study concluded that "deep geological disposal is technically feasible and does not present any particularly novel rock engineering issues" (p. 69). Furthermore, both Sweden and Finland are in advanced stages of designing and licensing for geological repositories for spent fuel, suggesting its feasibility as a deployable approach.

Public Acceptance. The effort to terminate Yucca Mountain illustrates the challenges to public acceptance at the local and state levels. Various agencies acting under pressures tied to a lack of public support took steps to delay or terminate the project by denying permits that are required for development of the site. For instance, Nevada has denied water rights to DOE that are necessary for the construction of a rail spur and facility structures at Yucca Mountain (GAO, 2009). While there are many reasons for the lack of official state support for Yucca Mountain, a relevant observation is that, despite state and local governments having little official role in decisionmaking related to Yucca Mountain, tenacious opposition within the state has nonetheless succeeded in blocking the development of the site thus far.

The centrality of public acceptance in repository development was emphasized by IAEA (2007b), which noted that a feasible solution has its technical dimension but that "an acceptable solution" always will have a combined technical and social dimension. In considering public acceptance issues, it might be instructive to compare the situation at Yucca Mountain to that of the Waste Isolation Pilot Plant (WIPP) in New Mexico. WIPP opened in 1999 and is the world's only permanent geological repository for long-lived radioactive waste (National Research Council, 2001). In contrast to Yucca Mountain, WIPP receives only transuranic wastes (protective clothing, tools, equipment, soils, and other items contaminated with transuranic elements), which, like spent nuclear fuel, are very long lived but have much lower radioactivity levels than spent nuclear fuel. This difference must be kept in mind when considering differences in outcomes concerning public acceptance in the two cases. Nonetheless, there might be useful lessons in the success of WIPP. As noted by the National Research Council (2001), one of the reasons that WIPP maintains local and state public support is its strong association with defense activities: WIPP accepts only defense-related waste, and 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. By analogy, it is conceivable that public support for a permanent geological repository for commercial spent nuclear fuel might be greatest in areas where local economies and loyalties are most aligned with nuclear power production.

Cost. GAO (2009) has estimated costs for the Yucca Mountain repository. Most costs are incurred as up-front capital costs and the totals are sensitive to the size of the repository. As noted in the introduction, the NWPA, as amended, limits the amount of waste that can be emplaced at Yucca Mountain to 70,000 MTHM. However, DOE (2008d) notes that this limit was not based on any technical considerations related to Yucca Mountain and that, legal limits aside, studies indicate that Yucca Mountain could hold three times or more this amount. Consequently, GAO (2009) provides two cost estimates. The first is for 153,000 MTHM that can be directly compared to the costs for on-site storage and centralized interim storage. In this case, GAO estimated that it would cost between $41 billion and $67 billion (in 2009 dollars) through 2151 to construct and operate a repository at Yucca Mountain. The second estimate is for a case in which the Yucca Mountain repository is kept at the legally allowed maximum capacity of 70,000 MTHM. In this case, the repository would cost between $27 billion and $39 billion, but additional repository capacity will be needed (DOE, 2008d).

A funding mechanism for the establishment of a permanent geological repository has already been established through the NWPA. As of January 2010, the Nuclear Waste Fund contains $24 billion (Holt, 2010). The fund has been accumulating monies through the collection of a fee of one mill ($0.001) per kilowatt-hour of nuclear-generated electricity imposed on power generators and accrued interest on the unspent balance in the fund. As of 2008, it has been estimated, 80 percent of the funds required to finance a repository will come from the Nuclear Waste Fund. The additional 20 percent will come from appropriations to cover the costs of DOE-managed spent nuclear fuel and high-level waste and will be paid for by federal taxpayers (GAO, 2009).

Comparison of Technical Approaches

In this section, we compare the four technical approaches in terms of the five criteria identified earlier. The relative implications of the different technical approaches are summarized in Table 2.3. The evaluations are necessarily qualitative, and there is considerable uncertainty for several factors, particularly those for the advanced fuel cycle, for which there is little basis with which to evaluate criteria. The intention is to identify major distinctions between technologies for each criterion.[16] The reasoning behind the assessment presented in Table 2.3 is provided in this section.

Table 2.3
Evaluation of Technical Approaches to Managing Spent Nuclear Fuel

Criterion	Continued On-Site Storage	Centralized Interim Storage	Advanced Fuel Cycle	Permanent Geological Disposal
Safety risk	Low	Low	Uncertain	Low
Security risk	Low	Low	Uncertain, potentially low	Low
Technical obstacles	Low	Low	High	Moderate
Public-acceptance challenges	Moderate in general, but higher at decommissioned sites	Low near nuclear power plants, but likely to be higher near proposed interim storage sites	High at site-specific level and likely high unless permanent geological disposal resolved	High at site-specific level, but much lower nationally
Cost	Low	Low	High	Moderate

[16] Since the analysis is qualitative, there is little meaning to comparing evaluations in different rows for a given alternative; that is, for example, “low” safety risk has no relative meaning compared to “low” security risk.

Safety

In terms of safety, there is little difference between continued on-site storage and centralized interim storage. Extended on-site storage might require repackaging of spent fuel, which could create additional exposure risk for workers. While centralized interim storage might provide some safety benefits by consolidating waste, they are likely to be small. Because the storage technology is essentially identical in both cases, the primary safety difference is related to the transportation of spent fuel to a centralized interim storage location. As noted in our evaluation, however, transportation of spent nuclear fuel is considered quite safe and therefore not an important safety factor in decisionmaking.

We consider permanent geological disposal to be comparable to on-site storage and centralized interim storage in terms of safety. While emplacing waste assemblies and backfilling and sealing a repository involve more waste movement and opportunities for package failures, the subsequent isolation of the waste from human contact provides some safety benefit over having them accessible on the surface, particularly in the very long term, when the uncertainties about the reliability of institutional control and maintenance of surface storage increase substantially.

The safety of advanced fuel cycles with complex fuel reprocessing is less clear. In a general sense, converting spent nuclear fuel from an inert solid encased in metal cladding to a heterogeneous mix of more–biologically and –environmentally accessible chemical forms provides opportunities for increasing environmental and worker safety risks. The experience with conventional reprocessing shows that safety is a serious concern and that careful management is required to maintain safe conditions. New, experimental fuel reprocessing methods can be expected to be accompanied by a host of new safety concerns. Hence, the advanced fuel-cycle option fares less well in terms of safety than on-site storage, centralized interim storage, or permanent geological disposal.

Security

The primary security concerns regarding spent–nuclear fuel management are theft of fissile materials for use in a nuclear weapon and the theft of radioactive waste materials for use in a radioactive dispersal device ("dirty bomb"). Several studies have discussed the risks of nuclear proliferation; analyzing these in detail is beyond the scope of our analysis. The key point that such risk analyses have that is relevant to our study is that the fissile material (primarily plutonium) in spent nuclear fuel is largely inaccessible to would-be thieves because it is dispersed in a solid matrix of uranium oxide and very radioactive fission products. The combination of being physically and chemically mixed with other materials and shielded from tampering by the high radioactivity of those materials provides a strong deterrent to theft and subsequent use for malevolent purposes. Thus, on-site storage, centralized interim storage, and permanent geological disposal, in which the plutonium remains part of the spent-fuel package, are inherently more proliferation-resistant than an advanced fuel cycle, in which the plutonium is separated from the other spent-fuel components. Among these, permanent geological disposal has the added security benefit of being isolated from human contact. Thus, even if a malicious agent were willing and able to separate plutonium from spent nuclear fuel, it would also have to employ a time-consuming and easily detectable earth-moving effort to extract the spent fuel from the repository.

The various U.S. and international initiatives exploring advanced fuel cycles all have minimizing nuclear-proliferation risk as a design criterion. A key design goal is to never isolate plutonium during the spent-fuel reprocessing and recycling process. The technical approaches are still under development, and the extent of proliferation resistance those approaches offer remains uncertain. An additional safeguard provided by some international initiatives is that spent-fuel reprocessing and recycled-fuel fabrication could, in principle, be limited to a selected set of countries that would provide fuel services to the rest of the world. This way, whatever proliferation risks that exist in the reprocessing approach ultimately adopted would exist only within a confined group of trusted operators.

Technical Obstacles

Spent nuclear fuel has been stored on reactor sites since the beginning of commercial nuclear power generation. The materials and methods for dry-cask storage are well established, and the transfer of spent-fuel assemblies from storage pools to casks is well under way. The technology for centralized interim storage is essentially identical to that of on-site storage. Technical obstacles to transferring all spent nuclear fuel to dry-cask storage for continued on-site storage or centralized interim storage are expected to be minimal. Even if casks were determined to have flaws or other problems develop, repackaging the spent-fuel assemblies into new casks would not involve any special technical challenges.

Developing and loading a permanent geological repository, while a vastly more involved engineering undertaking than surface storage, does not present any particularly challenging technical obstacles either. The main difference, rather, is the financial commitment and time involved.

The technical obstacles to advanced fuel cycles are greater. Since more-sophisticated fuel cycles are still in the research and development stages, there are, by definition, numerous technical challenges yet to be solved.

Public Acceptance

Although some publics are not entirely comfortable with continued on-site storage of spent nuclear fuel, moving spent fuel to centralized interim storage sites, even if away from populated areas, would likely face increased challenges by introducing the question of transportation safety and by rekindling the unresolved question of where the spent fuel will ultimately be permanently disposed of. Development of advanced fuel cycles would likely face much greater difficulties with public acceptance because of the major infrastructure development required and the questionable environmental and worker safety and health record of reprocessing operations. The immense public-acceptance difficulties associated with permanent geological disposal are well known from the history of Yucca Mountain, although the WIPP experience suggests that those difficulties are not insurmountable.

Cost

The cost results from GAO (2009) for on-site storage, centralized interim storage, and permanent geological disposal discussed earlier are summarized in Table 2.4. Each estimate is for 153,000 MTHM of spent nuclear fuel. For on-site storage and centralized interim storage, the estimates include the capital and operating costs for storing the spent fuel for 100 years. For permanent geological disposal, the costs cover construction and operation through 2151, which covers loading and sealing the repository. The results show that costs for on-site storage and centralized interim storage are comparable, while the cost for permanent geological disposal is substantially greater. Based on the midpoints of the cost ranges, the cost of permanent geological disposal is about 2.4 times more than surface storage for 100 years. A greater cost for permanent geological disposal is, of course, expected, as surface storage will still require subsequent management steps in the longer term (perhaps some repackaging after 100 years and presumably permanent geological disposal in the long run). Table 2.4 does not include a cost estimate for an advanced fuel cycle because of the great uncertainty in estimating costs for advanced fuel cycles. As noted earlier, advanced cycles are far from the commercial stage, and there is no telling what sort of advanced fuel cycle would eventually be implemented, making it exceedingly difficult to estimate potential costs.

An important caveat about using cost as a criterion for comparing different spent-fuel technical approaches is that waste management represents only a small fraction of the total cost of generating electricity from nuclear power plants. This differs from the case for the other criteria, for which the primary concerns for nuclear power overall are

Table 2.4
Comparison of Costs for Three Technical Approaches to Spent–Nuclear Fuel Management (2008 dollars)

Technical Approach	Cost ($/kgHM)
On-site storage	85–220
Centralized interim storage	98–190
Permanent geological disposal	270–440

SOURCE: GAO (2009).

NOTE: kgHM = kilogram of heavy metal. All estimates are for 153,000 MTHM. Storage costs are for 100 years. GAO used a range of discount factors in a Monte Carlo simulation framework to develop its discounted present value cost estimates. GAO (2009, Appendix IV) provides a detailed discussion of its discounting assumptions and methodology.

rooted in questions about waste management. The total generation costs for nuclear energy are dominated by nuclear power plant costs (building, operating, refurbishing, and decommissioning). In a detailed analysis of the implications of 13 different fuel cycles, the NEA (2006) found that the waste-management cost accounted for only 1 to 5 percent of the total generation cost. Therefore, even though the costs of different spent-fuel management options can differ considerably, the effect of this difference on the total generation cost is small. The situation for advanced fuel cycles is somewhat different in that implementing an advanced fuel cycle would require substantial investment in research, commercialization, and infrastructure development that goes far beyond waste management. Hence, while the waste-management costs of an advanced fuel cycle might be manageable, there are substantial costs involved in getting to the point at which an advanced fuel cycle could be used.

CHAPTER THREE

Review of Institutional, Statutory, and Regulatory Arrangements

In this chapter, we examine the hypothesis that the current institutional arrangements for decisionmaking on the disposition of spent nuclear fuel are a primary reason that the U.S. government has been unable to implement a policy that mandated developing a permanent repository at Yucca Mountain by 1998. We focus on the academic literature and other published sources for arguments as to whether public acceptance and other factors relevant to the decisionmaking process would be likely to change if political discourse and decisions were to take place within a different institutional framework.

This chapter begins with a brief overview of the current institutional framework for making and implementing policy concerning the disposition of spent nuclear fuel: the underlying premises, objectives, legal context, organizational roles and responsibilities, and processes, including the engagement of the public. We next review the literature for a critique of the current framework. We evaluate the framework in terms of two classes of criteria: organizational competence and capacity (e.g., incentives, conflicts of interest, expertise) and decision process attributes (e.g., conflict resolution, transparency, credibility, equity, fairness, timeliness, and efficiency). With this evaluation in hand, we then discuss implications for restructuring the existing institutional framework responsible for regulating, managing, and storing spent nuclear fuel.

Overview of Current Institutional Framework

By the late 1970s, nuclear power, which had received a boost from the oil price shocks of the 1970s, had lost much of its luster.[1] Nuclear power projects consistently cost much more, often several times more, than initially projected, and were much more expensive than fossil fuel alternatives (MIT, 2003, p. 38). Public acceptance fell, especially following the 1979 accident at the Three Mile Island nuclear plant near Harrisburg, Pennsylvania. As costs of electricity from coal, natural gas, and oil remained much lower than nuclear electricity throughout the 1980s, the nuclear industry believed

1 There have been no new construction starts for nuclear plants since 1977 (EIA, 2009).

that keeping the nuclear power option open, once economic conditions became more favorable, would depend on the public perceiving that the United States was on a path toward "solving" the waste problem—meaning that permanent disposal of spent nuclear fuel was the endpoint (L. Carter, 1987; Stewart, 2008). Up until the mid- to late 1970s, both utilities and government had been assuming that reprocessing would take care of most of the spent fuel and that relatively small volumes of waste would need to be buried along with high-level waste and waste from defense programs. However, that assumption turned out to be wrong as the full economic costs and safety requirements of reprocessing became more apparent and as the Carter administration and Congress judged proliferation risks to be too high (National Research Council, 2001). The Carter administration's decision to foreclose reprocessing left on-site storage, centralized retrievable storage, and permanent disposal as the only available alternatives.

This decision forced Congress to come to grips with the question of whether it was acceptable to the public to leave spent fuel and other high-level nuclear waste in temporary storage at power plants or at centralized facilities—in effect, transferring the costs and risks of permanent disposal to future generations. Congress decided that the answer was no and that the United States needed to move expeditiously toward a permanent repository. As a consequence, Congress passed the 1982 NWPA, which established the institutional framework that is still in place today. In the NWPA amendments of 1987, Congress went one step further and placed limitations on on-site storage, centralized surface storage, and monitored retrievable storage for fear of undermining achievement of the long-term goal of permanent burial. These concerns ultimately drove all of the key policy choices regarding program goals, timetables, and regulatory structures (Stewart, 2008).

The NWPA had two primary objectives:

- Site and build two permanent repositories, one in the East and one in the West, with the first to begin receiving waste in 1998.
- Transfer risk and associated liability of owning and disposing of high-level waste or spent fuel from plant owners to the federal government.

Congress viewed each of these steps as critical to increasing public acceptance of nuclear power and lowering legal barriers to new plant construction. On-site storage would be an interim measure until the repository was ready to receive waste. The NWPA, as amended, altered the first objective by focusing all resources on the Yucca Mountain site to the exclusion of other candidate sites.

The NWPA, as amended, and the Energy Policy Act of 1992 (Pub. L. 102-486, §801) spelled out institutional roles and responsibilities:

- DOE would conduct research, characterize, and recommend sites; prepare site license applications; design and build repositories; accept waste and transport it to repository sites; and operate repositories.
- NRC would license new plants, on-site storage, and repositories according to its safety criteria and oversee decommissioning of plants and storage facilities.
- The Environmental Protection Agency (EPA) would set radionuclide-release standards to limit human exposure to radioactivity from repository operations over the long term, initially defined by EPA as 10,000 years, later extended by EPA to 1 million years, following a court decision that EPA had not followed the recommendations of the National Academy of Sciences.[2]
- The National Academy of Sciences would make technical recommendations concerning disposal standards to EPA (a provision added in the 1992 Energy Policy Act).
- Industry would initiate applications for new nuclear plants and expand on-site storage as needed but otherwise would not play a role in repository siting or licensing. Nuclear power generators would pay fees based on electricity (not waste) produced, in return for a contractual commitment from DOE to begin accepting their waste in 1998. Those fees, which public utility commissions have allowed to be passed through to ratepayers, are deposited in the Nuclear Waste Fund.
- States where waste was generated would have virtually no role in the repository siting and licensing processes, while the state where a repository was under consideration (only Nevada, following the 1987 amendments to the NWPA) would conduct its own additional site-related research and contribute to DOE's technical review process but without any authority to alter the course of study or repository design. The host state could exercise its option to oppose DOE's site-suitability finding but, to block the finding, would have to also persuade the majority of both houses of Congress to support its opposition.
- Local authorities would work cooperatively with the state on research and technical review but otherwise have no special standing.

Several features of this arrangement are worth noting. First, DOE plays multiple roles, as a research agency, project advocate, project manager and licensee, waste owner, and facility operator. Second, in the Energy Policy Act of 1992, Congress built in a role for two regulators, EPA and NRC, with the unprecedented role of the National Academy of Sciences recommending the specifications of the radionuclide-release standard. Finally, the act laid out a process of successive steps for DOE to follow, with few opportunities to adapt or change course along the way as DOE learned more about the site, adjusted views about storage needs, or responded to public concerns (National Research Council, 2003).

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2 *Nuclear Energy Institute v. EPA*, 373 F.3d 1251 (D.C. Circuit 2004).

Assessment of the Current Framework

One simple metric that could be used to judge the success of the current institutional framework is whether it led to the opening of a permanent waste repository by 1998, which was the core objective of the NWPA. Clearly, the system failed to meet the deadline, although the process has managed to pass through some of the act's wickets for the proposed repository at Yucca Mountain, notably the environmental-impact statement, the site-suitability determination in 2002, and the submission of the site license application to NRC in 2008 (DOE, undated). The state of Nevada's political leadership remains unalterably opposed (Nevada Office of the Attorney General, 2009; Reid, undated). As a first-of-its-kind project, it is difficult, in the absence of a fair comparison, to say whether the process thus far has cost too much. Nonetheless, the federal expense thus far of reaching a site-suitability determination and producing a site license application reached $13.5 billion in 2007 dollars, far higher than costs anticipated in 1982 (DOE, 2008a).

The overarching policy question is whether Congress should continue to stand by this process and let it play out however slowly, or instead make changes now in the face of substantially different economic and environmental conditions than existed in 1982. With the administration's current position to withdraw its application for a license for Yucca Mountain from NRC, it is unclear whether the existing policy of focusing on permanent disposal, as prescribed by the NWPA and largely maintained by Congress over the past 25 years, has been supplanted by a de facto policy of extended on-site storage. Stewart (2008) and Ewing, Singer, and Wilson (2009) both argue that, because the fundamental premise of national policy regarding spent fuel has changed, the institutional framework must change in response. Change could come in the form of amended law, revisions in regulation and policy, restructured or new organizations, altered financial arrangements, or technological advancement. Which form of change to undertake depends critically on national objectives and a systematic assessment of the strengths and weaknesses of current arrangements.

In this section, we evaluate the capacity and performance of the current institutional framework beyond the simple question of success or failure in siting a repository, with the aim of establishing a baseline against which to consider the value of change. We propose two categories of evaluative factors:

- organizational competence and capacity
- performance of decision processes.

Organizational Competence and Capacity

In the organizational-competence-and-capacity category, we consider four criteria that bear on the question of whether the key agencies of DOE, NRC, and EPA have, at a minimum, the competence and capacity to fill their respective roles:

- alignment of organizational incentives with the national objective of managing the nation's spent-fuel inventory
- ability to carry out responsibilities without internal conflicts to agency missions
- technical expertise and capacity
- leadership within the organization.

How these agencies stack up against these criteria has a bearing on whether some of the proposed changes in the institutional framework would make much of a difference. If they do, in fact, have the competence and capacity to perform as expected, then it is reasonable to conclude that efforts to change the institutional framework might be best focused on policy and the decisionmaking processes intended to implement the policy. In contrast, if these organizations clearly are operating with major deficiencies, then the case for more-radical organizational change is stronger. In this section, we discuss each agency in terms of its organizational competence and capacity, drawing largely on our review of the literature and discussions with technical experts and decisionmakers familiar with the policy history associated with spent nuclear fuel.

Department of Energy. Experts with whom we talked and our own assessment suggest that DOE's mission is compromised by a fundamental conflict of interest between the research enterprise of siting a repository and its statutory responsibility to meet an aggressive deadline for waste acceptance, set by Congress without full cognizance of its technical feasibility. Under current law and by design, the federal government, with DOE as its agent, continues to have a strong incentive to site a permanent repository as soon as possible to avoid the very situation in which it finds itself today, of paying large penalties to utilities because of its inability to accept the spent fuel and associated liability since 1998, when the repository was supposed to begin operations (Garvey, 2009).

Although framed as a first-time, large-scale engineering project in the NWPA, the project depended critically on repository siting and design processes that relied on major research programs. Research often leads to new insights and surprises, as it did at Yucca Mountain (National Research Council, 1990). New findings about the character of the site and implications for repository construction and operations led to major changes in DOE's operating assumptions and engineering designs (NWTRB, 1997, 1998, 2000, 2008). In the context of the prescribed public participation process under the National Environmental Policy Act (Pub. L. 91-190) and other public interactions, such changes had the unintended effect of further undermining DOE's credibility, already compromised by the fact that Yucca Mountain was the only site under consideration following the 1987 amendments to the NWPA. Further, it took DOE many years to shake off its strong institutional culture of secrecy and offer more transparency in its actions (National Research Council, 2001), but, by that time, the Nevada public's trust had already been lost (National Research Council, 2003). DOE's funding for repository development came through the annual congressional appropriations process, which kept DOE accountable to Congress but, at the same time, foreclosed its control over the timing of the process. Funding over the years has been uneven (Holt, 2010). Operating under the gun of the mandatory waste-acceptance provisions of the NWPA, DOE nonetheless made some changes in the program as new information came to light but ultimately continued to push ahead toward the site-suitability determination and license application, even if research suggested that even more changes would be needed, further undermining public belief in Nevada that the process was fair and technically sound.

In terms of technical expertise, DOE has a core of qualified program and project managers but has nonetheless needed to rely almost entirely on the use of outside contractors under the direction of a management and operating contractor—first TRW Environmental Safety Systems, then Bechtel SAIC Company, and finally, at the end of 2008, USA Repository Services ("URS-Led Team Selected to Manage Yucca Mountain Project," 2008). DOE also made extensive use of scientific resources in the national laboratories, mainly Lawrence Berkeley, Livermore, Sandia, and Los Alamos. Throughout the years of the program, there has been a natural tension between DOE project managers and its contractors—who were focused on meeting DOE's statutory deadlines—and the research community, which sought greater understanding of the physical processes that would determine the site's suitability for isolating the radionuclides from the environment for more than 10,000 years. Reports emanating from the National Research Council over this time spoke of the negative consequences of the U.S. program's focus on artificial deadlines and unrealistic timelines at the expense of broadening public acceptance and gaining technical credibility (National Research Council, 2001, 2003).

Leadership at DOE headquarters and within the program changed multiple times throughout the process as presidential administrations changed. The relevance of these leadership changes to the failure of the program is difficult to assess. DOE institutionally remained committed to implementing the NWPA and following through on the repository siting process under all administrations.

U.S. Nuclear Regulatory Commission. In the literature we examined, we could find no instances in which NRC's integrity or technical competence regarding its role in the regulation of spent nuclear fuel has been called into question. This includes NRC's ongoing licensing and oversight role of on-site storage pools and dry-cask storage, as well as its review of the Yucca Mountain site license. NRC is an independent agency with five Senate-confirmed commissioners. Its independence provides NRC with some insulation from political pressures, and its mission leaves little room for conflicts of interest: "to regulate the nation's civilian use of byproduct, source, and special nuclear materials to ensure adequate protection of public health and safety, to promote the common defense and security, and to protect the environment" (NRC, 2010a). In 2000, then-chair of the commission, Richard Meserve, stated,

> the NRC does not have a promotional role with respect to the use of nuclear technology. Nonetheless, we do recognize that the way in which we perform our jobs can have a significant impact on public attitudes. We must both be, and be seen, as a rigorous, independent and capable regulator. The significance that the Commission places on its obligations in this regard is reflected in the fact that we have identified enhancing public confidence in the NRC as one of our four major goals in our strategic planning. (Meserve, 2000a)

Because the five-year terms of NRC commissioners are staggered, continuity of leadership at NRC is ensured over the long term, although the commission has often functioned without its full complement of commissioners. Continuity of operations at NRC comes through its stable civil service workforce, although its aging technical staff will pose challenges if the commission's workload increases substantially above its current levels (Murphy, 2007).

Up until the 2002 site-suitability decision, NRC played a background role through staff-level consultations with DOE as the department prepared the voluminous documents to support the site license application. NRC had been reviewing DOE's 2008 license application for Yucca Mountain, a process that was halted by DOE in March 2010; if NRC had proceeded to issue a favorable review, its decision would have cleared the way for construction of the repository at Yucca Mountain to begin (NRC, 2008a).

U.S. Environmental Protection Agency. EPA had only one role under the NWPA, and that was to set human health and environmental radiation protection standards for repositories. Following enactment of the Energy Policy Act of 1992, EPA was directed to set a radiation dose standard specifically for Yucca Mountain, consistent with technical recommendations from the National Academy of Sciences. The agency had no internal conflicts of interest with this narrowly defined role. However, EPA did seek consistency with its standards for the WIPP in New Mexico, which has a completely different regulatory process from the one prescribed for Yucca Mountain, as well as other statutory mandates, such as the Safe Drinking Water Act (Pub. L. 93-523). Indeed, the Safe Drinking Water Act requirements led EPA to conclude that a separate groundwater standard was necessary in addition to an individual protection and human intrusion standard. After a process that extended for almost 20 years, including a major court challenge by industry and other interveners to EPA's 2001 proposed groundwater standards and its proposed regulatory compliance period of 10,000 years, EPA finally issued its amended final standards in September 2008 (EPA, 2008).

We found no source in the literature that called into question the technical competence of the EPA staff in its standard-setting process for Yucca Mountain. The big difference between EPA's standard approach and the site-specific Yucca Mountain standards is the extraordinary time frame—1 million years to cover the period of peak risk as recommended by the National Academy of Sciences—and the large uncertainties about exposure pathways and endpoints over that time. EPA recognized the large uncertainties about long-term performance, opting to use a probabilistic analysis, and ultimately convinced NRC that NRC's traditional standard of proof in licensing of nuclear plants of "reasonable assurance" was inappropriate for long-term repository performance. NRC accepted this point in 2001 and adopted EPA's approach, "reasonable expectation."[3]

Leadership changes within the Office of Air and Radiation at EPA, which has had responsibility for the Yucca Mountain standards, have occurred as administrations have changed but have had no identifiable impact on EPA's decisionmaking process with regard to the Yucca Mountain standards.

Performance of Decision Processes

The second category of evaluative factors applied to the existing institutional framework relates to the performance of the several decision processes embedded in the NWPA and subsequent amendments. Key processes include the DOE process of reaching a recommendation on site suitability, the EPA process of setting a regulatory release standard for the proposed site, and the NRC process for reviewing and approving (or not) the site license application. These criteria are meant to capture the various dimensions of public acceptance:

- ability to resolve conflicts among various parties and stakeholders
- transparency to enable informed public participation
- credibility, leading to the public's trust in information coming from the process
- fairness and equity, leading to the public's trust in the outcomes of the process
- timeliness in reaching a decision
- cost-effective use of public and private funds to reach a decision.

By necessity, we restrict our assessment of these criteria to the more-significant higher-level features of the decisionmaking processes that have been the focus of advocates of change.

Conflict Resolution. By any measure, the current decision processes have led to many conflicts that are proving difficult or impossible to resolve. The most significant conflict has been between DOE and the State of Nevada. Even prior to the passage of the 1987 NWPA amendments, most of Nevada's political leadership began to mount its opposition to the designation of Yucca Mountain as the nation's first waste repository (Nuclear Waste Project Office, 1998). In 2002, following the procedures laid out in the NWPA, the state issued a formal notice of disapproval to DOE's site-suitability determination (Guinn, 2002). In the absence of workable conflict resolution mechanisms under the NWPA, the venue for resolution shifted to the courts in 2002 at the time of the site-suitability determination and has remained there ever since. Even

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[3] U.S. Environmental Protection Agency, Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada; Final Standard, 40 CFR Part 197, June 13, 2001, and later amended September 30, 2008; for history of the standard-setting process, see also GAO (2000).

though the court, in 2004, rejected every argument against the legitimacy of the site designation,[4] the conflict was still not resolved. Nevada has launched other lawsuits against DOE related to the radiation standard, water rights, transportation routes, public access to information, and oversight funding.[5]

A second key conflict was between EPA and DOE. DOE spent billions of dollars developing and refining a waste-isolation concept that depended on assumptions about the effectiveness of natural and engineered barriers—before knowing exactly what performance standard for radionuclide exposure EPA would ultimately promulgate and the courts would uphold. Prior to issuance of the final EPA standard in 2008 (EPA, 2008), DOE objected to EPA's standard setting on three grounds: First, DOE believed that EPA's proposed exposure standard of 15 millirem per year was unnecessarily restrictive compared to the widely used 25-millirem-per-year standard applied to other nuclear facilities (a position taken independently by NRC as well); second, DOE, supported by a National Research Council study (National Research Council, 1995), objected to EPA's added requirement on groundwater quality, which EPA believed it was compelled to include under the authority of the Safe Drinking Water Act (EPA, 2008); and third, DOE objected to the extension of the compliance period to 1 million years, as recommended by the National Academy of Sciences and enforced by the District of Columbia Court of Appeals.[6]

Transparency and Credibility. Because of the close correlation between a public agency's transparency in the conduct of its business and its credibility in the eyes of the public, we consider these two criteria together. In the context of repository siting, transparency refers to the public's ability to understand the processes, research findings, and programmatic consequences of DOE's activities. In the early 1980s, DOE held many hearings associated with the development of the siting guidelines and the nomination of sites in the initial stages of the siting process prescribed in the 1982 NWPA. Hearings allowed for public comment but little to no dialogue between DOE officials and the public. Following the selection of the three sites for characterization in 1986 (Yucca Mountain in Nevada, Hanford Reservation in Washington, and Deaf Smith County in Texas), DOE offered to enter into negotiations for a consultation and cooperation agreement with each of the three affected states (as provided in the act), but none of them accepted the offer. Not until the formation of the U.S. Nuclear Waste Technical Review Board (NWTRB) following the 1987 NWPA amendments did DOE's Yucca Mountain management leadership begin to have regular interactive contact with the Nevada public at NWTRB public sessions.

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4 *Nuclear Energy Institute v. EPA*, 2004.

5 Nuclear Waste Project Office, 1998.

6 It should be noted that EPA extended the compliance period, not because it believed that doing so was appropriate but because the National Academy of Sciences recommended that it do so.

DOE's lack of transparency, particularly in the early days of the program, had the predictable consequence of further undermining DOE's credibility in the eyes of the Nevada public and the environmental community (La Porte and Metlay, 1996). DOE had a difficult time reconciling its role as a research agency with its role under the NWPA as the applicant and advocate for a site license and ultimately its role as owner of the waste. As a consequence, DOE maintained positions on repository design issues that it later had to reverse when new research clearly showed their undesirable consequences. Examples include erroneous initial assumptions about infiltration rates of water through the unsaturated zone (NWTRB, 2000), the integrity of the stratum of volcanic tuff in which the repository was originally to have been placed (NWTRB, 2000), and the suitability of the alloy used for the waste canister (NWTRB, 1998, 1999, 2003). In each case, DOE changed course when subjected to pressure by NWTRB, Nevada, and others. These reversals further undermined the Nevada public's trust and confidence in DOE, with a similar effect on the interested scientific community as well.

Notably, NRC adopted a very different stance toward transparency and public engagement (Meserve, 2000a, 2000b), recognizing the connection between public acceptance of risk and public perceptions of the credibility of the action agency (La Porte and Metlay, 1996). As a consequence of its actions over the past two decades with regard to spent-fuel disposition, NRC is not subject to the same questioning of its credibility among the public as DOE.

Fairness and Equity. Congress considered regional equity important enough in 1982 that it called for two repositories, one in the East and one in the West. However, by 1987, political expediency won out over regional equity, leading to Yucca Mountain as the only candidate site—in spite of the fact that most of the spent fuel in the United States is generated from and stored at nuclear plants in the East and Midwest and none in Nevada (NRC, 2010b). Since 1987, no other site has been under consideration. Not surprisingly, Nevada strongly perceives that the designation of Yucca Mountain as the sole site for evaluation in 1987 was unfair, with no legitimate way for DOE to find the Yucca Mountain site unsuitable in a process with only one option. Not even the existence of NWTRB, authorized in the 1987 NWPA amendments to lend credibility to the site-characterization process, could overcome the basic fact that Yucca Mountain was the nation's only choice of a repository site. Other states with significant on-site storage at nuclear plants could also legitimately argue that they were being unfairly required to bear a burden.

Timeliness. DOE did not meet a single deadline set by Congress in the NWPA. Not only did the failure to meet deadlines further undermine DOE's credibility; it led to DOE's failure to meet its obligation under the act to accept waste from the utilities in 1998, leading to lawsuits and damage judgments, which continue to the present (Garvey, 2009). In retrospect, the deadlines imposed by the NWPA were unworkable, given the complexity of the technical undertaking. EPA also missed its original deadline to issue a site-specific exposure standard. In 1992, Congress obligated EPA to create a standard one year after receiving guidance set forth by the National Academy of Sciences, a process that ended up taking 15 years. The National Academy of Sciences issued its report in 1994 (National Academy of Sciences, 1994), but it was not until 2001 that EPA first issued its proposed standard. Following a legal challenge that led to an appellate court ruling in 2004, EPA issued its final standard on September 30, 2008 (EPA, 2008).

Missing deadlines is both a symptom and cause of failure in the NWPA process. Congress set the NWPA deadlines without fully understanding the complexity of the research tasks, the complications with engineering a repository as salient geological and other scientific facts were still coming to light, and the consequences of the absence of public acceptance.

Cost-Effective Use of Public Funds. It is difficult to assess the cost-effectiveness of a one-of-its-kind undertaking. What can be said is that the federal government, drawing on funds in the Nuclear Waste Fund collected from ratepayers, has spent more than $13 billion (in 2007 dollars) since 1982. Utilities have sued DOE for damages, resulting in DOE's inability to accept spent fuel as a consequence of missing the NWPA's 1998 deadline for opening a repository. DOE estimates that settlement of these cases will result in accumulated costs of around $12.3 billion by 2020 (GAO, 2009). If Yucca Mountain is not opened by 2020, the federal government will have spent approximately $25 billion in total.

Considerations for Moving Forward

Given the current national policy concerning siting a permanent repository, our brief assessment indicates that DOE, EPA, and NRC have largely performed as Congress directed them to do—albeit at a much slower pace than originally anticipated, vastly higher costs, and, in the case of DOE and EPA, with a few large errors (e.g., DOE's major miscalculation in repository design to match Yucca Mountain's physical properties; EPA's missteps on the standard). However, what seems to have mattered more in the failure to produce a successful outcome than technical and managerial competence were

- the collapse of the original NWPA consensus formed around the idea of an eastern and western repository in 1986 that led to the sole focus on Yucca Mountain in the 1987 NWPA amendments
- poorly aligned incentives and institutional conflicts of interest within DOE that led to a loss of public confidence and decisionmaking gridlock
- the overarching policy under which DOE labored after the 1987 amendments to the NWPA: driving toward repository siting at the expense of a more comprehen-

sive plan for aboveground, long-term storage, and a more incremental approach to repository development with multiple sites.

Changes in the institutional framework need to be carefully considered in the context of national policy on management of spent fuel. In Chapter Four, we discuss four policy strategies, each of which will require varying degrees of change in institutional arrangements to enable their successful implementation. However, based on our analysis, two major institutional changes merit closer examination to determine whether they would facilitate whatever course of action Congress and the administration choose to pursue, including the status quo:

- resolution of the problem of ownership of spent fuel and financing of expanded on-site storage facilities in the absence of a permanent geological repository
- reassessment of organizational responsibilities in managing spent fuel.

All spent-fuel management strategies discussed in the next chapter require utilities to maintain and expand on-site storage for an extended duration. As such, the government's liability for failing to take possession of spent fuel at operating and decommissioned plants will continue to mount unless some change in policy or practice is made. Utilities did not make provisions for funding the expenses associated with long-term storage in the same way that they did using escrow accounts to handle plant-decommissioning costs. As Ewing, Singer, and Wilson (2009) note, the absence of dedicated funds available to utilities to manage the long-term storage of spent fuel is an historical artifact of the presumption in the NWPA that spent fuel would move relatively quickly from reactor sites to a permanent repository prior to the decommissioning of the plants. That presumption was indeed central to forcing government action on the difficult tasks of siting and licensing.

The federal government cannot unilaterally change the terms of the contracts with the utilities with regard to waste acceptance; the contacts remain in force and 71 breach-of-contract claims have already been filed against DOE (Garvey, 2009). However, Ewing, Singer, and Wilson (2009) describe a set of changes to the NWPA that could be implemented that would offer utilities an alternative approach to funding long-term on-site storage and, at the same time, would relieve the government of the obligation to take title of the spent fuel immediately. Under an arrangement with strict NRC regulation, the government would place the funds required for long-term storage into separate interest-bearing escrow accounts for each reactor. Ewing, Singer, and Wilson suggest that the terms under which this change would occur could vary for existing plants (optional) and relicensed or new plants (compulsory). Utilities would continue to own the waste, but they would also gain control of the funding and have incentives to manage waste storage efficiently, including transport from decommissioned to still-operating plants. To this end, Congress and the states could allow utilities more flexibility about where spent fuel could be stored for longer-term surface storage, to the extent that economies and safety could be improved by consolidation at some sites within a state or even across state lines (Ewing, Singer, and Wilson, 2009). This might be particularly useful as some nuclear plants are decommissioned, as expected over the next several years. Changing this one area of the law would provide the government and industry with significantly more flexibility and potential cost savings than presently exists, and removes a significant impediment to strategies that require more time for research, development, and implementation.

These changes in funding and managing on-site storage might be necessary but still insufficient to fully resolve the waste-acceptance issues. For this approach to be feasible, the public and the industry are likely to still need credible assurances in law that progress will be made toward the federal government taking ownership and possession of spent fuel (by developing a repository, centralized interim storage facility, or recycling facility) over the next several decades through dedicated funding and transparent, sustainable, and competent organization and management.

To further mitigate the effects of eroded public trust and of poorly aligned incentives within the existing framework, it is likely that any new spent-fuel management strategy will have more credibility if it is managed by a new organization outside of DOE. Such an organization could take several forms: public, private, or a public-private hybrid like, for example, a public corporation. The idea of a public corporation and permanent fund to support it has recently been suggested by Ewing, Singer, and Wilson (2009) and Stewart (2008) but was advanced publicly in 1985 by the Advisory Panel on Alternative Means of Financing and Managing Radioactive Waste Facilities (1984). That study, updated by DOE in 2001 (DOE, 2001), found that the independent federal authority model (such as the U.S. Postal Service and Federal Deposit Insurance Corporation) would provide the most flexibility and adaptability and has generally been used in cases when the government has a monopoly on a distinct service. This model might be very appropriate for managing commercial spent nuclear fuel. No fundamental changes would be required for NRC or EPA at this point in time. In taking steps to move the management of the repository program outside of DOE, Congress would be acting on the presumption that the public trust, once lost, cannot easily be regained by maintaining the status quo of organizational design. The validity of this position cannot be proved, but La Porte and Metlay (1996) and the numerous social science sources they cite lend credence to this view.

In the next chapter, we outline several policy alternatives for managing spent nuclear fuel in the United States, each of which has implications for considering changes in the institutional framework under which the United States is currently operating. The current arrangements, put in place in 1982, have turned out to be more inflexible than enabling for an undertaking as fraught with uncertainty and subject to changing public perspectives as spent–nuclear fuel management. That observation alone is grounds for reexamining options for altering the institutional framework.

CHAPTER FOUR

Policy Implications of Alternative Strategies

Following the recent termination of funding and the withdrawal of the NRC license application for Yucca Mountain, a new national spent–nuclear fuel management strategy must be crafted. While many of the basic technical and institutional elements from which a new strategy will be developed are well understood, these elements can be combined in different ways, and the policy implications of different combinations differ in important ways. To help inform policy deliberations, we have constructed four basic spent-fuel management strategy proposals the United States could choose to pursue. The proposed strategies are not intended to represent a comprehensive menu of options but rather were chosen to span a wide range of approaches and to elucidate some important policy implications of different approaches. The strategies are summarized in Table 4.1. For each strategy, we summarize the key near-term (five to ten years) actions related to storage, fuel recycling, and disposal.

Table 4.1
Strategies for Spent–Nuclear Fuel Management

	Near-Term Actions Related to		
Strategy	**Storage**	**Recycling**	**Disposal**
Expeditiously proceed with Yucca Mountain	Maintain on-site storage until Yucca Mountain available	Maintain current level of advanced fuel-cycle research	Open Yucca Mountain
Develop centralized interim storage in conjunction with permanent geological disposal	Develop centralized storage facilities	Maintain current level of advanced fuel-cycle research	Pursue alternative sites
Pursue advanced fuel cycles	Continue expansion of on-site storage or develop centralized storage facilities	Aggressively expand advanced fuel-cycle development efforts	Do not commit to any particular time plan or site
Maintain extended on-site storage	Continue expansion of on-site storage	Maintain current level of advanced fuel-cycle research	Do not commit to any particular time plan or site

Each of these strategies is examined considering the criteria and analysis presented in preceding chapters. For each strategy, we discuss the conditions or priorities that would need to prevail in order for it to be favored and possible institutional changes that would facilitate its success. We also consider the implications of each alternative for the future of nuclear power in the United States and for the welfare of future generations.

Policies for spent nuclear fuel might have an important influence on the future role of nuclear power in the United States. An important factor contributing to the nuclear industry's reluctance to invest in new nuclear capacity has been its inability to divest itself of the ownership and physical possession of spent fuel (Nuclear Energy Institute, 2010; McCullum, 2009). Several state and local governments have a similar view and limit the amount of waste that can be stored at locations or require that a permanent repository be established before approval for a new nuclear power plant will be granted. California, Oregon, and Wisconsin, for example, have requirements that a permanent repository be opened before new nuclear power plants can be built (Farsetta, 2009). At the same time, the high costs and difficulties of obtaining insurance for new nuclear power plants are also impeding the growth of nuclear power. Thus, the influence of a particular spent-fuel management policy on the future of nuclear power must be interpreted in the context of these and other important influences.

The strategies also have different implications for future generations. Each defers differing amounts of decisionmaking, technical development, and both financial and political costs to future generations. This deferral raises the issue of intergenerational equity: A given alternative might trade near-term benefits for longer-term problems or, conversely, might pose costs and require difficult decisions to be made in the near term, leaving fewer problems for future generations. In considering timing and intergenerational trade-offs, it is important to keep in mind that, regardless of the strategy chosen, on-site storage will continue for at least the next decade, and, in some strategies, it would continue for many decades. At a minimum, continued on-site storage will be necessary until a centralized interim storage facility, permanent geological repository, or spent-fuel-recycling facility becomes available. Although it is impossible to predict timescales with confidence, past experience and the current state of technology suggest that licensing Yucca Mountain or a centralized interim storage facility would take at least a decade, a new permanent geological repository would take two or more decades, and implementing advanced fuel cycles would take many decades. Moreover, even after the capacity for centralized storage, disposal, or recycling becomes available, on-site storage will continue—either because removal from power plants would be deferred after facilities were available (e.g., to maintain access to spent fuel for possible recycling or to reduce the heat output of the waste before disposal) or simply because it would take decades to eliminate the backlogs of spent fuel built up in storage by the time removal began (DOE, 2008b; Office of Technology Assessment, 1985).

Expeditiously Proceed with Yucca Mountain

This alternative entails reactivating the Yucca Mountain repository project, making the site able to receive spent nuclear fuel as quickly as possible. While this strategy entails expeditiously preparing Yucca Mountain to accept spent fuel, it does not necessarily imply proceeding with immediate disposal; some or all spent fuel could be retrievably stored at the Yucca Mountain site or continue to be stored at nuclear power plants. Until 2009, this was the strategy being pursued by DOE to comply with the NWPA and hence represents a "stay-the-course" alternative. Our analysis shows that current geological disposal technologies and plans can be safe, secure, technically feasible, and intermediate in cost. The principal drawback is the strong opposition in Nevada to using Yucca Mountain as a spent-fuel repository.

Proceeding with Yucca Mountain would be the fastest route to removing a major impediment to the expansion of the nuclear power industry in the United States. Licensing Yucca Mountain and beginning the process of taking title of spent fuel being stored by utilities would fulfill the disposal contracts, which would increase the nuclear power industry's willingness to invest in new generating capacity. In addition, the existence of a licensed permanent geological repository could increase the flexibility for spent-fuel management by facilitating the development of centralized interim storage facilities: Private and government efforts to develop centralized interim storage facilities have been blocked on the argument that, without a licensed repository, any interim storage facility is susceptible to becoming a de facto permanent storage facility. Thus, proceeding to construct and begin operating a repository at Yucca Mountain is compatible with an extended period of storage for as much of the spent fuel as desired, pending resolution of uncertainties about its ultimate disposition.

Development of a permanent geological repository in the near term leaves a relatively smooth course for future generations: Safety and security are high, spent-fuel disposal would no longer stand in the way of new nuclear power plant development, public-acceptance issues will have been dealt with, and major costs will have been paid. It is therefore consistent with an important tenet of spent-fuel management policy up to this point—that the generation that benefited from the activities that produce nuclear waste should bear the burdens of disposing of it. A potential drawback is that this alternative entails proceeding with current disposal technologies and plans. However, a convincing case has not been made that current spent-fuel disposal technology is inadequate, and, in any case, it is not clear that a disposal technology that is safer than required by current regulations will make much of a difference in reducing the political difficulties in siting a repository. A related argument is that technology might advance to the point at which it is advantageous to recycle spent fuel, but, once permanently disposed of, its residual energy potential will no longer be available. However, the final closure of Yucca Mountain is not scheduled to occur for more than 100 years, and this could be delayed if desired.

Proceeding with Yucca Mountain would therefore be most favored when the top priorities are solving the spent-fuel management problem as quickly as possible rather than leaving it for the future and paving the way for growth of nuclear power in the United States. While the existing institutional framework was designed to support this alternative, the Yucca Mountain project's tumultuous history, ultimately leading to its termination, indicates that institutional changes will likely be needed to resurrect it. It is possible that there is no institutional change now that would eliminate the firm opposition in Nevada, but transferring the responsibility for building and operating the Yucca Mountain repository from DOE to a new organization—a different government agency, a government corporation, or a private corporation—could help to reestablish public trust in the project.

Develop Centralized Interim Storage in Conjunction with Permanent Geological Disposal

This strategy represents a two-part approach that entails transferring spent fuel to one or more federal centralized interim storage facilities and developing a permanent geological repository for final disposal. This approach is attractive because it is flexible and provides a potentially much simpler alternative to direct disposal at Yucca Mountain for rapidly fulfilling disposal contracts. Compared to a permanent geological repository, a centralized interim storage facility is technically simple, can be built quickly, and is reversible. Our analysis indicates that centralized interim storage is affordable and technically straightforward. Sweden, for example, has been operating an underground interim storage site since 1985. Compared to on-site storage, centralized interim storage might generate small cost and safety benefits due to economies of scales associated with centrally securing and managing larger quantities of spent fuel. This potential benefit needs to be weighed against the safety issues associated with transporting waste to and from the interim storage site.

This strategy could be implemented in different ways. In principle, it could be implemented within the bounds of the NWPA. This would be difficult, however, because of constraints imposed by the 1987 NWPA amendments. Specifically, construction of a centralized interim storage facility (called a monitored retrievable storage facility in the NWPA) cannot begin until after a permanent geological repository has been licensed, the only option for that permanent geological repository is Yucca Mountain, and the storage facility capacity is capped at 10,000 MTHM until Yucca Mountain begins accepting spent fuel (after which the cap increases to 15,000 MTHM).

In the context of the current situation, the most glaring difficulty with implementing the strategy this way is that it negates one of the strategy's key attractions: the ability to honor disposal contracts and stimulate new nuclear power without having to wait for a permanent geological repository. Once a repository is licensed, much of the concern about contracts will have been alleviated. An additional difficulty is the capacity limitation. Even if the link to a repository license were lifted, this limitation, while high enough to allow spent fuel from currently shut-down nuclear power plants to be removed, means that the bulk of spent fuel could not be transferred to the federal government.

Alternatively, modifying the NWPA in a number of ways would provide more flexibility in implementing this strategy. One important change would be to allow the construction of one or more centralized interim storage facilities before finalizing a permanent geological repository. This would allow the federal government to take possession of spent fuel while the future of Yucca Mountain is deliberated or a new permanent geological repository is found. This approach was endorsed by the Monitored Retrievable Storage Review Commission (1989), and DOE unsuccessfully pursued this approach through the 1980s and 1990s. Given the apparently dim prospects for Yucca Mountain in the near future, it might be worthy of reexamination now. A second helpful change would be to lift the capacity limit for centralized interim storage. In this case, all spent fuel could be removed from nuclear power plants relatively quickly. Finally, modifying the NWPA to allow permanent geological disposal outside of Nevada would provide the opportunity to consider alternative sites for permanent geological repositories. While this would delay the licensing of a permanent geological repository, implementing centralized interim storage would alleviate much of the urgency in moving forward with a permanent geological repository.

A counterargument to this strategy, noted in the previous section, is the opposition to interim storage stemming from the fear that, without a plan for permanent disposal, interim storage could extend indefinitely. Despite several attempts, past efforts to establish both federal and private centralized interim storage facilities have repeatedly failed. However, it could be argued that the policy environment has changed significantly enough, in response to the need to lower global emissions of greenhouse gases, to warrant revisiting this option.

The priorities that would favor this strategy are similar to those for proceeding with Yucca Mountain. It would similarly be a route to fulfilling the federal government's contractual obligation to take title of waste as quickly as possible, which would remove a major impediment to the expansion of nuclear power. However, it would take longer to finally dispose of the spent fuel in a permanent geological repository, thereby delaying final resolution of the spent-fuel management problem. Because it allows for consideration of multiple sites and technological advances in geological disposal that might be available over the next few decades, this alternative is slightly more favorable, albeit fundamentally similar, with regard to safety, security, and technical feasibility.

There are some additional policy considerations if Yucca Mountain continues to be viewed as an unworkable solution and the process of site selection, characterization, and approval of a permanent geological repository is renewed. Given the extent to which the NWPA underestimated the time required to site and develop a permanent geological repository, it might be prudent to move away from a schedule-driven approach and toward the staged approach advanced by the National Research Council (2003). As with the Yucca Mountain alternative, creating a new organization to manage site selection and development of both centralized storage and permanent geological repositories could help reestablish public trust in the project. Along with transferring much of the past responsibility of the DOE Office of Civilian Radioactive Waste Management to a new organization, the roles of other agents, including the EPA, NRC, National Academy of Sciences, and industry, could be reexamined and revised if changes were deemed beneficial. It might also be helpful, for both technical and acceptance reasons, to return to the multiple-site-evaluation and -development concept originally envisioned in the NWPA. Technically, this would allow continued investigation into alternative geological settings: Granitic, shale, salt, and clay formations are all being seriously investigated by other countries (IAEA, 2001; National Research Council, 2001). From a public- and political-acceptance perspective, considering and developing multiple sites might alleviate some of the sense of injustice perceived when Congress narrowed the choice to Nevada.

Pursue Advanced Fuel Cycles

In this strategy, resources would be concentrated on developing an advanced nuclear fuel cycle that would allow recycling of spent nuclear fuel. Advanced fuel-cycle technologies that offer a large reduction in spent-fuel waste volumes are still in the research and development stages. Substantial time and federal investment would be required to implement this strategy, especially if the goal of the advanced cycle is to reduce, by orders of magnitude, the concentration of transuranic species in spent-fuel waste. Initially, this alternative would entail large increases in research and development efforts to establish the technical feasibility and the technology base required for developing key process subsystems and components. This would be followed by multibillion-dollar expenditures to select and demonstrate the fuel cycle at a commercial scale. From there, it would involve development of substantial new infrastructure, including spent-fuel reprocessing plants, new uranium-enrichment and fuel-fabrication facilities, and a new fleet of advanced reactors. A permanent geological repository would still be required for residual high-level waste and long-lived low- and intermediate-level wastes, although efforts to site and approve a repository could be safely deferred for decades. Because of the long implementation time required to develop and deploy the infrastructure for an advanced fuel cycle, surface storage of spent fuel would likely continue for decades longer than in either of the direct-disposal alternatives discussed earlier.

The implications of pursuing an advanced fuel cycle differ substantially from those of other alternatives. The technical obstacles are great, the cost is high, and public acceptance is likely to be poor due to the additional processing facilities that would need to be built. Because of the technical challenges, there is great uncertainty about the likelihood of success and the safety and security of this alternative. It could therefore leave future generations with an unworkable or unacceptable solution. It also leaves open for future generations the task of siting and developing a permanent geological repository, including associated political- and public-acceptance concerns. An advanced fuel cycle would reduce the demand for raw uranium resources; the reduction depends strongly on the particular fuel-cycle design and could range from about a factor of two to more than two orders of magnitude, which would become important if uranium prices rose substantially. In a strategy that involved surface storage and cooling of separated high-level waste for 100 to 200 years, an advanced fuel cycle that greatly reduces the amounts of actinides in the waste stream could also reduce the required capacity for a permanent geological repository by a factor of ten to 20 compared to that for direct disposal of spent fuel. An associated increase in long-lived intermediate-level waste, which also requires geological disposal, would erode some of this volume reduction. Despite eliminating the long-lived transuranic elements from the waste, an advanced fuel cycle would have little benefit in terms of decreasing the effective radiation dose or timescale over which this dose occurs.

These differences mean that the conditions that would favor pursuing an advanced fuel cycle are very different from those favoring a direct-disposal approach. Because of its potential impact on waste volume and uranium consumption, an advanced fuel cycle would be most attractive if reducing permanent geological repository volumes and extending the lifetime of uranium resources were the highest priorities. These priorities, in turn, would be most important under a scenario with strong support for a major expansion of nuclear power.

The advanced fuel-cycle alternative would likely delay disposition of spent fuel for much longer than either of the two preceding policy alternatives that center on geological disposal. Thus, this strategy would become much more attractive if the problem of spent-fuel ownership were to be resolved early on, as opposed to being put on hold until an advanced fuel cycle were implemented. In particular, it is quite likely that centralized interim storage would need to be implemented at some point long before spent-fuel recycling becomes available.

This alternative is sufficiently different from the current U.S. policy that changes in the institutional framework would undoubtedly be needed. An advanced fuel cycle would introduce new types of facilities, new types of wastes, and new worker responsibilities and exposures. The existing nuclear industry regulatory framework associated with facility licensing, environmental protection, security, and worker safety and health would therefore need to be carefully examined to determine whether it was flexible and comprehensive enough to support advanced fuel-cycle operations. International sharing of resources and knowledge of national regulatory authorities could avoid duplication of work and promote best practices (NEA, 2009a). Developing and operating an advanced fuel cycle would also require government support for new research and development, education and training, and infrastructure development. A major ramp-up in advanced fuel-cycle research would require increased funding and benefit from strong coordination among programs, although major changes in organizational structures or roles might not be necessary. Education and training efforts would need to be expanded to reverse trends stemming from the stagnation of nuclear power programs. Strong government support will be important for building and operating the new advanced fuel-cycle infrastructure. A successful transition to an advanced fuel cycle would require careful division of responsibilities between industry and government through the design and application of policy tools, such as research and development support, regulations, tax credits, and loan and insurance subsidies.

Maintain Continued On-Site Storage

In this strategy, spent fuel would remain on site at nuclear power plants until some external event triggered further action. This is essentially the same as the "no-action" alternative considered by DOE early on in its environmental-impact statement on options for the management of radioactive waste (DOE, 1980). It differs from a permanent storage option, such as that considered by DOE in its environmental-impact statement on the Yucca Mountain repository (DOE, 2008b), in that there is an understanding that the spent fuel must eventually be disposed of in a permanent geological repository. In this "wait-and-see" strategy, the United States chooses to defer decisions and investments in further spent-fuel management activity until prompted by some external event. Possible triggering events could include significant progress in spent-fuel management in another country, increased urgency to stimulate new nuclear power capacity as existing nuclear power plants are decommissioned, or a significant increase in uranium-ore prices that stimulates demand for spent-fuel recycling.

Our review of the literature indicates that further on-site storage is safe, secure, and the least expensive; faces few technical obstacles; and would have the fewest political- and public-acceptance difficulties. Requirements for repackaging stored fuel are unresolved but are not an important technical challenge. In most cases, there is no pressing space limitation or other urgent reason to remove spent fuel from nuclear power plant sites. Maintaining on-site storage would also allow time to further develop technologies for permanent geological disposal and advanced fuel cycles.

These attractive near-term aspects would have to be weighed against significant challenges in the longer term. The federal government would remain in breach of disposal contracts and continue to accrue liability for compensation to nuclear power generators that should have been able to turn over spent fuel to the federal government in 1998. This liability might already be tens of billions of dollars (Garvey, 2009). In doing nothing to address the transfer title of spent fuel to federal government, this strategy would make no progress toward expanding the role of nuclear power and could send a negative message to generators about future prospects and increase uncertainties about attempting to license new reactors. In addition, this strategy would leave important burdens for the next generation. The existing uncertainty about how best to manage spent fuel, including the job of siting and developing a permanent geological repository, will remain and need to be resolved in the future. Pursuing this strategy therefore runs counter to the tenet that spent-fuel management should be dealt with by those who generate it, which has guided spent–nuclear fuel management policy thus far.

This alternative is favored under conditions in which the uncertainty surrounding the technical feasibility, environmental risk, safety, security, public acceptance, or cost of any other alternative is viewed as too great, compared to that of continued on-site storage, to warrant moving forward. Such conditions imply that, rather than having a moral obligation to not leave spent-fuel disposal to future generations, the United States is not yet prepared to take action on this issue and therefore that the best action is to wait.

Strategies similar to this have been considered and rejected several times in the past, including DOE's environmental-impact statement on options for the management of radioactive waste and subsequent record of decision (DOE, 1980, 1981), the Senate's recommendation for approval of the Yucca Mountain site (U.S. Senate, 2002), and DOE's environmental-impact statement on the Yucca Mountain repository (DOE, 2008b).

Implications for Spent-Fuel Management Policy

The preceding discussion illustrates that the different strategies can have widely differing implications in terms of societal priorities for spent–nuclear fuel management, trade-offs of responsibilities between current and future generations, and the future growth of nuclear power. To help compare the different alternatives, we have summarized these implications in Tables 4.2–4.4.

The priorities that would favor the adoption of each strategy differ in some important ways. Designing an appropriate policy strategy therefore requires consideration of the nation's objectives for spent-fuel management and vision for nuclear power generation. As shown in Table 4.2, if the view that we are obligated to provide a solution for disposing of spent fuel as quickly as possible prevails as a top priority, either because we believe that the generation that benefited from the activities that produce nuclear waste should bear the burdens of disposing of it or because we need to demonstrate the feasibility of the entire fuel cycle before further commercial development of nuclear power, then proceeding with Yucca Mountain is the best choice. This strategy would also fulfill the federal government's obligation to take possession of spent fuel and pave the way for the expansion of nuclear power. If the main priority is more oriented toward enabling the expansion of nuclear power and a premium is placed on confidence in

Table 4.2
Priorities That Would Favor Different Strategies

Strategy	Priorities Consistent with Strategy
Expeditiously proceed with Yucca Mountain	Provide a solution for spent-fuel disposal as quickly as possible Fulfill disposal contracts and enable expansion of nuclear power
Develop centralized interim storage in conjunction with permanent geological disposal	Fulfill disposal contracts and enable expansion of nuclear power Increased confidence in decision consensus and repository performance
Pursue advanced fuel cycles	Strong support for major expansion of nuclear power Reduce permanent geological repository volumes and extend the lifetime of uranium resources
Maintain extended on-site storage	Uncertainty concerning any other alternative is too great to warrant moving forward at this time

the decision process related to repository development and performance, then the two-stage centralized interim storage–permanent geological repository strategy becomes more attractive. Strong support for a very large increase in nuclear power, which could place a premium on permanent geological repository capacity and uranium resources, would favor recycling spent fuel with an advanced fuel cycle. Finally, if uncertainty regarding repository performance, safety and security (e.g., during transportation), cost, or public and political acceptance looms large enough, then continued on-site storage might be appropriate.

When considering the implications for future generations (Table 4.3), a clear distinction is that the different strategies reach different states in terms of progress toward final disposition of spent fuel. Proceeding with Yucca Mountain or the centralized storage–permanent disposal strategy provides a solution for final disposal in the relatively near term. Depending on the details of the technology chosen, pursuing advanced fuel cycles could leave future generations with significantly decreased repository capacity requirements. However, a substantial investment would be needed to realize those benefits; the reprocessing and recycling facilities would need to be themselves sited and would then have to operate for a very long period of time; and other waste products generated from the processes might require disposal as well. Continued on-site storage leaves final disposal for the future.

A related distinction is the level of uncertainty left for future generations. The Yucca Mountain and centralized storage–permanent disposal strategies leave the least uncertainty. Pursuing the advanced fuel-cycle alternative would provide future generations with more information on the viability, safety, and security of this approach. But if this is done at the expense of pursuing centralized storage or a permanent repository, future generations would have less information than might be desirable to implement these more-conventional and -likely options. Also, considering the different potential

Table 4.3
Different Strategies' Implications for Future Generations

Strategy	Implications for Future Generations
Expeditiously proceed with Yucca Mountain	Solution for spent-fuel disposal in place Locked into current technology Precludes retrieval of buried resources when sealed
Develop centralized interim storage in conjunction with permanent geological disposal	Solution for spent-fuel disposal in place Precludes retrieval of buried resources when sealed
Pursue advanced fuel cycles	Possible decreased demand for repository capacity and uranium resources Uncertainty about likelihood of success, safety, and security Must maintain extended on-site storage or develop centralized interim storage Must still site and develop a permanent geological repository
Maintain extended on-site storage	Must maintain extended on-site storage, even when plants are decommissioned Must site and develop a permanent geological repository

approaches and objectives of advanced fuel-cycle technologies, government policy on selecting candidate approaches would need to set clear objectives regarding wastes if this strategy is to ultimately provide large benefits in terms of reducing repository requirements. Maintaining continued surface storage prolongs the existing uncertainty about how best to manage spent nuclear fuel.

There are also differing implications for future fuel supplies, though these are probably less significant. Use of a permanent geological repository to dispose of spent fuel in the near term would eventually eliminate access to spent fuel should it become desirable to recycle it. Conversely, an advanced fuel cycle would reduce uranium demand. Given the uncertainty about the magnitude of nuclear energy production in the future, it is difficult to weigh the impact of these fuel-supply implications. Historical patterns in ore production of continued discoveries and decreasing costs suggest that fuel conservation might not be a particularly important consideration.

The implications of the different spent-fuel management strategies on the growth of nuclear power in the United States (Table 4.4) are clouded by the fact that future growth of nuclear power is sensitive not only to spent-fuel management but also to cost, risk, insurability, and public acceptance of nuclear power plants. The influence of spent-fuel management policy must therefore be interpreted in light of these other influences. Expeditiously proceeding with Yucca Mountain and the storage-repository strategies would have the greatest positive impact on the future of nuclear power because they would most swiftly allow the federal government to fulfill its contractual obligation to take possession of spent nuclear fuel. This would remove impediments to growth based on spent-fuel concerns. The advanced fuel-cycle strategy could help

Table 4.4
Different Strategies' Implications for the Future Growth of Nuclear Power

Policy Focus	Implications for Nuclear Power Growth
Expeditiously proceed with Yucca Mountain	Demonstrates the government's ability to take possession of spent fuel, paving the way for nuclear power growth in the near term
Develop centralized interim storage in conjunction with permanent geological disposal	Demonstrates the government's ability to take possession of spent fuel, paving the way for nuclear power growth in the near term
Pursue advanced fuel cycles	Unclear; might eventually clear the way for nuclear power growth if terms for continued storage are improved and states lifted moratoria on new plant construction
Maintain extended on-site storage	Does not facilitate nuclear power growth and might have negative impact

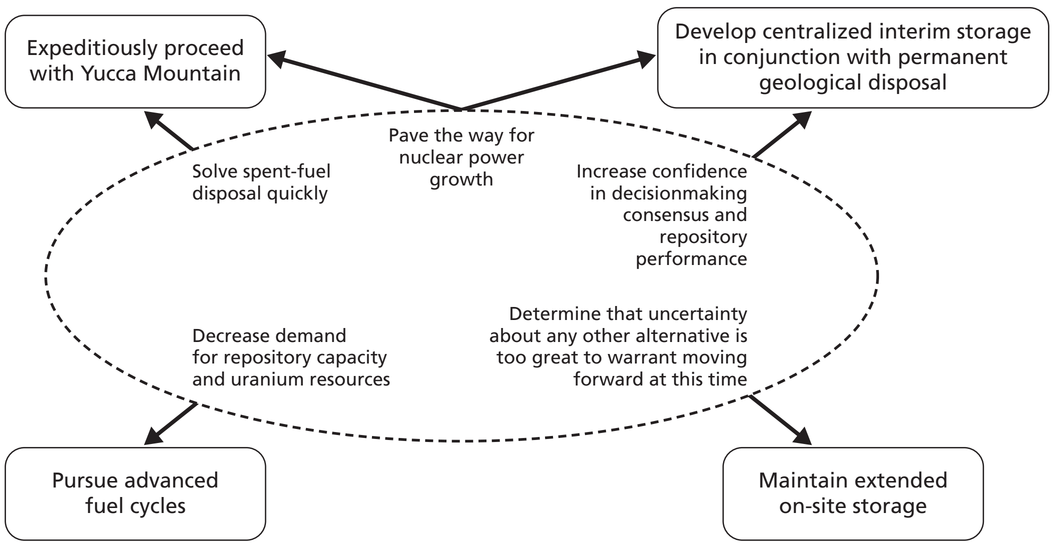
clear the way for new nuclear power plant development if it included mechanisms to improve the terms of ownership and financing of continued surface storage of spent fuel. Finally, in prolonging the indecision about spent-fuel management policy and potentially complicating new reactor licensing, continued on-site storage does nothing to facilitate growth in nuclear power and might have a negative impact.

Tables 4.2–4.4 summarize the important policy implications of the four strategies examined in this study. While other strategies could be developed by delving into more detail about the technical approaches and their combinations, the selected strategies are intended to span much of the range of options currently being considered. The selection of policy alternatives ultimately depends primarily on societal preferences about the disposition of spent fuel, the growth of nuclear power, and intergenerational trade-offs.

While the findings do not perfectly distinguish the different strategies according to unique societal preferences—some priorities are consistent with multiple strategies, and some strategies are consistent with multiple priorities—they nonetheless help restrict the range of combinations. The association between the strategies and several possible priorities is shown in Figure 4.1. Aggressively pursuing advanced fuel cycles is attractive primarily if constraints on repository capacity or uranium resources are important. Maintaining extended on-site storage is attractive only if all other options are deemed unacceptable. Proceeding with Yucca Mountain or the centralized storage–geological disposal strategies is most attractive when facilitating the growth of nuclear power and not leaving spent-fuel disposal for future generations are the top priorities; choosing between them depends on how important it is to increase confidence in decision consensus and repository performance.

This analysis highlights the implications of each strategy in the context of these societal preferences. Choosing a strategy thus entails assessing these preferences among stakeholders; it might be difficult to achieve a consensus. It is likely

Figure 4.1
Association Between Strategies and Possible Societal Priorities



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that no single strategy will satisfy all stakeholders in all three dimensions illustrated in Tables 4.2–4.4. However, in bringing the multitude of technical and institutional considerations together in the form of a limited set of preferences, we hope this analysis will contribute to consensus building and help guide that decisionmaking process.

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