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INTERIM STORAGE OF SPENT FUEL IN THE UNITED STATES

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■ **Abstract** At nuclear power reactors around the United States, quantities of spent or irradiated nuclear fuel are growing while owner-operator companies await the approval of a permanent storage facility. Some reactors have run out of space in their cooling pools and have had to resort to dry cask storage. The first half of this paper looks at the policy history of interim storage in the United States, discusses the current storage status at individual reactors, and then reviews the technologies available to deal with it. The second half of the paper considers the different options for dealing with this hazardous material in the interim, before a permanent high-level nuclear waste repository is opened, and examines the safety, security, transportation, economic, political, and other issues that bear on the choice of option.

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1. INTRODUCTION

The management and disposal of irradiated fuel from nuclear power reactors is an issue that burdens all nations that have nuclear power programs. None has implemented a permanent solution to the problem of disposing of high-level nuclear waste, and many are wrestling with solutions to the short-term problem of where to put the spent, or irradiated, fuel as their cooling pools fill. The United States is no exception.

Certainly, some aspects of the solution to the spent-fuel problem are specific to individual countries. Japan, for instance, has plans to recycle its spent fuel to extract plutonium for reuse in reactors. By comparison, the United States plans to throw away its spent fuel and not recycle it. Japan's domestic spent-fuel reprocessing facility is still under construction, however. With no place for the spent fuel to go, reactor cooling pools are beginning to reach capacity. In the United States, the progress on the as-yet-unapproved permanent repository site at Yucca Mountain, Nevada, has created a similar problem. As a result, while these countries, as well as others, develop a more permanent solution, they need to find an interim solution to the problem of spent-fuel storage.

US nuclear reactors have already produced over 40,000 metric tons (MT) of spent nuclear fuel, which currently reside on site at reactors. By the end of the lifetimes of the existing 103 currently licensed, operating reactors, the total amount will likely be over 80,000 MT. Still more will be generated due to reactor license extensions. None of these reactors is currently equipped with the capacity to store all the spent fuel they will produce over their lifetime. Many owner-operator companies expected that the spent-fuel problem would be resolved by now, as US law stipulated that the Department of Energy (DOE) would take title to the spent fuel and begin to move it to a repository by January 31, 1998. To relieve the burden of spent-fuel storage from individual nuclear reactors while they await the opening of a permanent repository, they will have to employ interim storage—or the reactors will have to shutdown.

For spent fuel that has exited the reactor core, until it enters a permanent repository (or is reprocessed), few storage options are available. It can remain at reactor sites or be transported to an away-from-reactor storage facility. At either location it can be stored in cooling pools (wet storage) or aboveground in casks or modular units (dry storage). Whether to use away-from-reactor or at-reactor storage and whether to use wet or dry storage are decisions made according to a variety of factors, including safety, security, transportation, costs, and politics. This paper examines these options and the factors affecting them in the context of the US spent-fuel situation.

Although the technical aspects of dry storage are relatively straightforward, the issue of whether to have at-reactor or away-from-reactor storage can become politically contentious. For example, during the years 1995–1999, strong majorities in both houses of Congress, responding to pressure from US nuclear owner-operator companies, supported legislation that would have mandated the rapid construction of a large, centralized, interim-storage facility near Yucca Mountain, Nevada. This plan faced strong opposition from the state of Nevada and a veto from President Clinton, and for the moment, it has been dropped in favor of at-reactor dry-cask storage. Nevertheless, the off-again/on-again history of the US debate over the interim storage of spent fuel suggests that in a new Administration and with a new Congress, the idea of centralized storage may be revisited again. Moreover, the debate over centralized storage will most likely heat up in the next few years when two privately managed and privately financed concepts for large interim-storage sites in the West move closer to actuality. Thus, the question of the relative merits of on-site versus centralized storage for spent nuclear fuel remains one of considerable importance.

This paper focuses on the current state of spent-fuel storage in the United States, with reference to storage policies in other countries. It covers the policy history pertaining to interim storage of spent fuel, discusses the current status of spent-fuel storage at reactor sites in the United States, considers the issues that affect interim-storage decisions and offers some conclusions on how these decisions are made. Although the focus of this paper is the situation in the United States, much of the discussion is pertinent to that in other countries, especially in terms of interim-storage decision making.

2. POLICY BACKGROUND

Federal policies on the interim storage of spent fuel originally piggybacked on permanent disposal legislation. Initially, the federal government [Congress and the Administration, including the DOE and the Nuclear Regulatory Commission (NRC)] and the owner-operator companies were the main players in interim-storage decisions. The field has expanded to include private-storage companies, Indian tribes, state governments, and the public. Changes in regulations promulgated by the NRC have also had an impact on the interim-storage landscape. Thus the options for interim storage of spent fuel have broadened somewhat and may continue to do so.

2.1. Legislative History

Interim storage of spent fuel is not a new concept. In the United States, it was initially proposed in 1972 by James Schlesinger, chair of the Atomic Energy Commission, as a way to accommodate high-level waste while a permanent repository was located and investigated (1). The original legislation that provided for the selection of a permanent repository for high-level waste, the Nuclear Waste Policy Act (NWPA) of 1982, envisioned the construction of a monitored retrievable storage (MRS) facility, as it was termed. To balance the responsibilities of storing and permanently disposing of nuclear waste, the NWPA prohibited the location of an MRS in any state under consideration as a permanent repository site (2). Under the NWPA, the secretary of the DOE was to submit a proposal for such a facility to Congress for approval of federal funds. Within five years, Congress amended the NWPA and some of the requirements changed. With the NWPA Amendments (NWPAA) of 1987, concerns that an MRS facility would become a defacto permanent repository were alleviated by the provision that construction of an MRS facility could only occur after the license for a permanent repository was granted (3). The main thrust of the NWPAA was to designate Yucca Mountain, located partially within Nevada Test Site boundaries (Figure 1), as the sole geologic repository for the nation's high-level nuclear waste. Again, as with the NWPA, the NWPAA distinctly forbade the construction of an MRS facility in the state of Nevada, the designated location for a permanent repository (4). The 1987 Act also established the office of the Nuclear Waste Negotiator, who was to negotiate with states or Indian tribes for an interim-storage site, and the MRS Commission, which was to report on the necessity of an interim facility to Congress by 1989.

The MRS Commission issued their report in 1989 (5). They determined that some type of interim storage would be needed but not a large-volume facility. They found that both an MRS option and a no-MRS option would meet safety requirements and that no single factor favored the use of an MRS facility (5). The Commission also noted that the undiscounted net cost of the MRS option might be less than no MRS but that the MRS option would be more costly on a discounted basis. They clearly stated that an MRS facility, linked to the licensing of the permanent repository as it was in the NWPAA, would not address any storage issues at all. The MRS Commission concluded by recommending that Congress authorize a federal emergency storage facility licensed to hold 2000 MT of spent fuel and an owner-operator-funded facility licensed to contain 5000 MT (5).

By 1992, 20 state, county, and tribal groups sent in applications for feasibility grants to assess whether they could host an MRS facility to the Office of the Nuclear Waste Negotiator (6). None of the applications was pursued by the applicants (7). As a result, in 1995, Congress did not reauthorize funding for the Negotiator, and the attempt to negotiate a solution to the waste problem was abandoned.

By the early 1990s, it became clear to the nuclear owner-operators that the DOE would not meet the 1998 deadline to begin moving spent fuel off reactor sites. A few, in fact, were already experiencing problems in obtaining public and

Figure 1 Map of nuclear power reactor locations in the United States. (*Star*) The location of Yucca Mountain and Jackass Flats, the proposed permanent and interim repository sites, respectively. (*Boxes*) The locations of the proposed private spent-fuel storage facilities—the Goshute Indian reservation west of Salt Lake City, Utah, and central Wyoming.

government support for the addition of at-reactor dry-cask storage. For the owner-operator companies the problem was clear: The DOE was required to dispose of the spent fuel, but until it ultimately took title to it, interim storage of spent fuel remained their responsibility. In response, the owner-operators began to pursue three parallel tracks: (*a*) They began lobbying for legislation to force the DOE to establish a centralized interim-storage facility at Yucca Mountain, (*b*) they formulated lawsuits to force the DOE to meet its obligations and pay damages to the owner-operators, and (*c*) they entered into negotiations with Indian tribes and other localities to develop privately managed interim-storage facilities.

From 1995 to 1999, Congress considered legislation forcing the interim storage of spent fuel at Yucca Mountain, Nevada. In the 104th and 105th Congresses, both the Senate and House versions of the bill passed their respective bodies, but the Senate bill did not receive the necessary two-thirds majority required to override a promised presidential veto. These bills required the construction of an interim-storage facility near Yucca Mountain that would begin to receive waste within five years or so from the passage of the bill (8, 9). The facility would have been licensed to accept 30,000–40,000 MT of spent fuel. The Clinton Administration continued to promise to veto any bill that would establish an interim-storage site at Yucca Mountain because they believed that a centralized facility located there would presuppose that the proposed permanent repository for high-level nuclear waste would be approved (10). In addition, construction of an interim facility at Yucca Mountain could erode political support for the permanent repository, not to mention the financial resources available (10).

In mid-1999, the DOE offered an alternative solution to the problem. The Secretary of Energy, Bill Richardson, proposed that the DOE take title to spent fuel while it remained at reactors and cover the costs of on-site dry storage. Senate leaders accepted this change and reformulated the bill so that the permanent repository was the focus instead of a centralized interim-storage facility. To ensure the opening of the permanent site in a reasonable time, they included language that forced shortened timetables on DOE and NRC decisions on the suitability of the Yucca Mountain site. Unfortunately, the bill contained language that opponents, including the Administration, considered unacceptable. In particular, it would have restricted the ability of the Environmental Protection Agency to set radiation standards at the permanent repository site (11). In February 2000, a Senate floor vote on the reformulated bill again failed to achieve a veto-proof margin of votes.

A number of owner-operator companies are involved in ongoing lawsuits with the DOE over its failure to meet the deadline. In one, Xcel Energy (formerly Northern States Power) is attempting to claim $1.6 billion in damages (12). A summary judgement for three New England reactors may result in awards of up to $268 million (13). At least 11 other cases are working their way through the US Court of Federal Claims, with claims totaling more than $4 billion (14).

2.2. Private-Storage Options

Three private-storage options have recently received serious attention, two on tribal lands and one on state land (Figure 1). Indian tribes have been the focus for interim-storage facilities because of sovereignty issues. As sovereign nations, the tribes can choose to do as they please with their land and can claim immunity from lawsuits (15). The two on Indian lands grew out of initial discussions with the Nuclear Waste Negotiator. Once the Negotiator's office was disbanded, the tribes began working directly with owner-operator companies, who then formed private consortia to open these facilities (16).

The Mescalero Apache tribe of southern New Mexico joined forces with 11 owner-operator companies led by Northern States Power to attempt to establish a 10,000-MTU facility on tribal land (17, 18). The decision to offer Mescalero land for an interim facility met with strong resistance within the tribe. The Mescalero's first vote on the interim facility decided against it, but a second, possibly coerced, vote decided for such a facility (15). The deal fell through in April 1996, when the owner-operator consortium suspended negotiations with the tribe (18).

Under serious consideration is another offer from a consortium of electric power owner-operators and an Indian nation, the Skull Valley Band of the Goshute Indians, in Utah. Eleven owner-operator companies signed an agreement with the tribe in December 1996 to open a spent-fuel storage facility on the Goshute reservation, 70 miles southwest of Salt Lake City. The group submitted a license application to the NRC on June 25, 1997, on which prehearings began in January 1998 (19, 20). The proposed facility would contain up to 40,000 MTU of spent fuel. To date, the NRC has issued a draft environmental impact statement and a safety evaluation report on the site, and neither has identified any significant problems with the site (21). If approved, the group hopes to open the facility by 2002 (20). Such an early date is unlikely based on the promised legal battles from the state of Utah, which vigorously objects to the proposed facility. For example, the governor of the state, Mike Leavitt, tried to derail the facility by taking title to the land surrounding the proposed facility in an attempt to create a state-owned "moat" that would prevent waste from being transported to the facility (22). The Bureau of Land Management, in response to Leavitt's actions, ruled that the state has no right to designate federal roads as state highways (23).

Yet another proposal for a privately owned interim facility is gaining momentum, the Owl Creek Energy project proposed for a site near Shoshoni, Wyoming. The Owl Creek project is directed by a consortium of members, including NAC International, an energy consulting and nuclear fuel storage and transport company; Parsons-Brinkerhoff and Woodward-Clyde, international engineering companies; Virginia Power; and NEW corporation, a Wyoming-based group (24). The local government is open to the project and strongly supported by the local state senator, Bob Peck (R-Riverton) (B. Peck, personal communication). The consortium plans to submit a license application to the NRC by 2000 and hopes to be operational by early 2004 (I. Stuart, personal communication). The future of the project remains uncertain, with the governor of Wyoming appearing to oppose the facility (25), and other state legislators, such as Mike Massie (D-Laramie), coming out against the project (M. Massie, personal communication).

2.3. Licensing Requirements

The NRC is responsible for licensing all spent-fuel storage facilities. Wet storage at reactors is licensed with the operating reactor. The NWPA required the NRC to rewrite its regulations so that on-site dry-storage facilities could be licensed under the general reactor license. In 1990, the NRC altered 10 Code of Federal Regulations (CFR) Part 72 to meet these requirements. As a result, at-reactor dry storage can be licensed under the reactor's general license (as long as the reactor is licensed under Part 50) or can be licensed separately (26). A general license applies only if the proposed dry storage meets certain requirements. For example, the site must meet NRC's seismic requirements, the concrete pad for the casks must be placed a certain distance from the site boundary, and the reactor must use NRC-licensed dry-storage systems and approved fuel types (27). If these requirements are not met, if the reactor shuts down, or if the facility is an away-from-reactor one, then the facility owners must seek a separate dry-storage license. Currently 9 dry-storage systems have NRC licenses, and 5 out of 13 reactors are using dry systems under their general license (28).

3. INTERIM-STORAGE POLICIES AND PLANS IN OTHER COUNTRIES

The way in which other countries deal with their spent fuel is dependent on the type of fuel cycle they use (open or closed) and how far along they are in permanently resolving the problem of high-level nuclear waste. In some countries, recent changes in government policies toward nuclear energy have also impacted the plans for spent-fuel storage. Below are compared the spent-fuel storage policies of several countries with relatively large nuclear power programs.

3.1. France

France reprocesses much of its spent fuel and as a result stores spent fuel awaiting reprocessing in a 14,400 MT pool storage complex in La Hague (29). It has one small dry-storage vault at Cadarache for exotic fuels (30). It is still in the initial planning stages for a permanent high-level nuclear waste repository. France is beginning to consider alternative interim dry-storage strategies for three reasons: (*a*) Reprocessing of spent fuel cannot keep pace with MOX (mixed oxide) fuel use, resulting in some spent fuel spending many years in the La Hague storage pool; (*b*) there are no plans to reprocess MOX fuel, thus soon there will be a need to store this material; and (*c*) most likely not all spent fuel will be reprocessed (31).

3.2. United Kingdom

The United Kingdom also reprocesses most of its spent fuel. Much of the spent fuel is in pools at the Sellafield reprocessing facility (29). [These pools are somewhat controversial because they use a once-through water flow that empties into the Irish Sea after conditioning (30).] All Magnox spent fuel must be reprocessed because it is unstable in water. Some of the advanced gas reactor fuel is stored on an interim basis in pools at the Sellafield facility. Spent fuel from the country's one pressurized water reactor is stored on site in the reactor's cooling pool, which has the capacity to store 30 years' worth of spent fuel (32). Only one reactor, Wylfa, currently uses short-term dry storage for Magnox fuels (30).

3.3. Germany

Until 1994, German policy required the reprocessing of all spent fuel. With the amendment of the German Atomic Energy Act in 1994, spent fuel can be directly disposed of, which, along with slow MOX use, has provided a need for interim storage of spent fuel. Germany currently has four away-from-reactor interim-storage facilities: Ahaus, Gorleben, and Julich, which employ dry-storage designs, and Griefswald, a wet-storage facility for Russian light water reactor type fuel [which will be converted to dry storage (30)] (33). As a result of public protests, little spent fuel is actually being moved into these facilities right now, especially the Gorleben facility, because of its controversial use as a potential permanent repository.

3.4. Sweden

Sweden no longer reprocesses its spent fuel and has established a dedicated away-from-reactor wet-storage facility, the central interim-storage facility for spent nuclear fuel (CLAB), located on the coast for ease of transportation (34). CLAB has space for 5000 MT of spent fuel and is currently two-thirds full (29, 34). CLAB is unique as a storage facility because it is an underground facility (located 25–30 m below the surface) with three pools made of concrete and lined with steel (30, 35).

3.5. Others

Because of delays in construction of its own reprocessing facility and slow usage of MOX fuel, many Japanese reactors are struggling to store their spent fuel. Three away-from-reactor storage pools exist, but only two are licensed for use. The Fukushima reactor is the only one in the country that uses on-site dry storage (30). The country is currently considering establishing some kind of away-from-reactor storage facility. Canada uses dry storage at reactor sites to handle its spent fuel (36).

4. INTERIM-STORAGE TECHNOLOGIES

Once enough neutron absorbers build up in irradiated fuel, it can no longer be used to create energy in a reactor and must be put into storage until it is cool enough for disposal or reprocessing. All spent reactor fuel is initially stored in deep cooling pools at reactor sites. After the spent fuel has cooled both thermally and radioactively, it can be transferred to a dry-storage system, if necessary. The time before spent fuel can be loaded into dry casks depends on factors such as the initial enrichment in U-235, the burnup of the fuel, the cooling time, and the operating history of the fuel. Most casks are licensed to use spent fuel that has cooled between 5 and 10 years, depending on the design (30). Any storage system, wet or dry, must meet four criteria: (*a*) It must avoid criticality, (*b*) it must ensure that radiation release is kept to the minimum required by regulations, (*c*) it must prevent unacceptable doses of radiation to workers, and (*d*) it must be retrievable (37). The following discussion describes the different types of spent-fuel storage available in the United States.

4.1. Wet Storage

All reactors employ wet storage of spent fuel on site. Cooling pools are fitted with stainless steel and aluminum racks that hold the fuel assemblies. These pools are lined with stainless steel to prevent leaking and are very deep; at least 2.5–3 m of water covers the tops of the assemblies to provide radiation shielding (38). These pools use deionized water that is usually attached to a purification system to decrease the reactivity of spent-fuel cladding with the water (39). They also employ cooling systems that use natural circulation to cool the spent fuel (38).

In the United States, the owner-operator companies' first response to diminishing storage capacity was to refit their pools with high-density storage racks. These racks allowed reactors to at least quadruple their storage capacity (38). Increasing the density of spent fuel in pools meant reevaluating the four criteria above and resulted in (*a*) neutron-absorbing materials being added to the racks themselves to control criticality, (*b*) recalculations of the radiation and thermal load to be borne by the pool, and (*c*) reevaluation of seismic analysis because of the increased structural load in the pool (38). For most US reactors, wet storage alone will not address all their storage needs.

4.2. Dry-Fuel Storage

Spent-fuel dry-storage designs are well-established technologies that have been licensed in the United States since 1985. Currently, 17 reactors employ dry storage to enhance their ability to meet their spent-fuel storage needs.[1] Another 13 sites have identified a vendor for dry storage (40) and are expecting to receive license approval from the NRC in the next few years (41). The NRC has currently approved nine storage designs (28).

An owner-operator has a fairly large choice of dry-storage systems. Those who want to add dry storage piece by piece, banking on the early opening of a permanent repository, can select from a number of different small-unit designs, such as metal casks, concrete casks, and dual-purpose cask systems. Seven US reactors use single-unit casks. These designs have outer shells, made of cast iron, forged steel, or a stainless steel and lead combination that acts as a radiation shield, and inner baskets that hold spent-fuel assemblies. Some designs are loaded vertically and some horizontally. These units use passive cooling to remove thermal radiation from the spent fuel and therefore require the spent fuel to cool substantially before loading. Some cask designs are loaded in the pool, then are dried and filled with either a vacuum or an inert gas such as helium to prevent spent-fuel degradation.

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[1] These reactors are Surry 1 and 2 and North Anna 1 and 2 (Virginia Power); Robinson 2 (Carolina Light & Power); Oconee 1, 2, and 3 (Duke Power); Fort St. Vrain (Public Service Co. of Colorado); Calvert Cliffs 1 and 2 (Baltimore Gas & Electric); Palisades (Consumer Power Co.); Prairie 1 and 2 (Northern States Power Co.); Point Beach (Wisconsin Electric & Power Co.); Arkansas Nuclear 1 (Energy Operations Inc.); and Davis-Besse (Toledo Edison Co.) (40).

Dual-purpose casks are similar to metal ones that can be used for storage and transportation. Currently, the NRC licenses only one dual-purpose cask design. In the future, the NRC may license multipurpose casks that can be used for storage, transport, and disposal of spent fuel (38, 40).

Having two different storage systems provides better economies of scale for those owner-operators that require a large amount of dry storage for a considerable amount of time. Concrete modular systems use stainless steel canisters, stored vertically or horizontally inside a larger concrete housing. Ten US reactors use a NUHOMS type design, which employs metal canisters in a horizontal concrete module (30). This system requires the use of a transfer cask and transporter to move the spent fuel from the cooling pool to the concrete housing. Modular vault systems provide metal fuel tubes in a vertical array housed in a concrete structure (38, 40). Only one such system is in use in the United States, at the shutdown Fort St. Vrain high-temperature gas reactor facility in Colorado.

4.3. At-Reactor and Away-from-Reactor Storage

Most spent fuel is currently stored at reactors in the United States. Both wet- and dry-storage designs are available for both at- and away-from-reactor storage. There are four facilities in the United States that in the past have accepted spent fuel for away-from-reactor storage. The Morris facility in Illinois and the West Valley Project in upstate New York were originally established as reprocessing facilities in the early 1970s. With the change in policy in the country and the poor economic outlook for reprocessing, these ventures were abandoned except for their spent fuel cooling pools, which remain today. Morris holds 3217 assemblies and West Valley holds 125 assemblies (42). The Idaho National Engineering Laboratory and the Hanford site, both facilities of the nuclear weapons complex, hold smaller amounts of civilian spent fuel [Hanford has seven assemblies and INEL 125 (42)]. Some owner-operator companies have transferred spent fuel from one reactor site to another or to away-from-reactor storage such as Morris. This practice has sometimes met with public protest. For instance, the state of Illinois banned transport of spent fuel to the Morris facility from out of state. A court subsequently ruled the ban on transport unconstitutional and some spent fuel was transported to the facility (38). For the most part, essentially no away-from-reactor facilities are currently available for use in the United States.

5. CURRENT STATUS OF SPENT FUEL AT US REACTORS

The problem facing many owner-operator companies is obvious: As power reactors age, they produce more spent fuel and spent-fuel storage capacity decreases. Indeed, at some plants, cooling pools have reached capacity and some spent fuel has been transferred to on-site dry-storage facilities. Although spent-fuel storage capacity is a pressing issue for owner-operator companies that need to find additional space, it should be noted that, to date, no reactors have shut down for lack of storage space. The question in the United States is how dire is the need for additional spent-fuel storage?

5.1. How Much Space Is Available?

Spent-fuel cooling pools at over half of the US power reactors are currently more than 50% full. Figure 2a and 2b present calculations of space remaining at reactors based on (*a*) calculations based on DOE and owner-operator data [owner-operator-based estimates of the total number of assemblies on site at individual reactors (43) divided by the licensed space in the reactors' pools (42)] and (*b*) owner-operator-based estimates [the total number of assemblies on site at individual reactors divided by their own estimates of remaining capacity in the pools (43)]. The owner-operator-based estimates suggest that as of 1998, slightly more reactors are over 50% capacity than the DOE and owner-operator data calculations show. For the most part, the DOE and owner-operator estimates in Figures 2a and 2b are slightly higher than those of the owner-operator companies because the licensed storage capacity instead of the owner-operators' estimates of storage capacity was used. The difference in the two capacity estimates lies in the fact the some of the licensed pool space may be occupied by other equipment.

5.2. How Rapidly Is the Space Disappearing?

Although storage space for spent fuel at reactors is decreasing, the question remains: How rapidly is this space disappearing? Most US reactors were originally designed with spent-fuel pools that would hold about two times the amount of fuel in the core of the reactor, because they planned to reprocess their spent fuel. A 1977 federal policy to defer indefinitely reprocessing of civilian spent fuel changed the owner-operators' plans, and to deal with the mounting spent fuel, they began to fit their pools with denser racks that hold more fuel. Currently, it is conventional wisdom (but not required by law) to hold a full-core's worth of space empty in the pool in case the core needs to be off-loaded for maintenance (J. Thorpe, personal communication). All calculations in this paper reserve space for a full-core off-load.

Figures 3a and 3b compare the results of three model predictions for the date of loss of spent-fuel pool space by reactor. As above, a pool is considered over capacity when the ability to off-load a full-core of spent fuel is lost. One model is supplied by individual owner-operators' estimates of loss of storage capacity at their reactors (43). Another model is supplied by the Office of Civilian Radioactive Waste Management (44) and is based on historical spent-fuel discharges, energy output, estimates of nuclear capacity growth, and plant operating performance. The third model is based on (*a*) my own calculations of storage capacity [based on estimating the number of years to off-load loss and adding them to the year 1998, with years to off-load loss calculated by subtracting the core size (42) from the available space in the pool—calculated by subtracting the owner-operator companies' estimates of the total number of assemblies on site (43) from the licensed space in reactors' pools (42)—and dividing this by the average actual discharge of spent-fuel assemblies per year]; (*b*) average annual spent-fuel discharge based on average annual historical discharge [calculated by using raw spent-fuel discharge data listed by reactor (J. Thorpe, personal communication); and (*c*) DOE and owner-operator data on licensed pool capacity. All models show that by 2010, over half of the reactors will have lost pool-storage capacity and will require some other form of storage.

5.3. Does Moving Fuel Off Site Prevent Owner-Operators from Buying Dry Storage?

A corollary to the question in the previous section is whether a centralized storage facility could relieve the burden of storage from individual reactors. In other words, will many reactors, regardless of efforts to ameliorate the space problem, still have to install dry-storage capacity? The above models do not include the schedule for transportation of spent fuel away from reactors to a permanent repository or an interim site. Using the transportation schedules for spent fuel at owner-operators around the country (45) and calculated annual spent-fuel discharges averaged for an owner-operator, it is possible to determine the impact of transport of spent fuel off reactor sites on the need of owner-operators to supply on-site dry-cask storage. Figure 4 shows the number of owner-operators that will need to purchase dry-cask storage for the cases of (*a*) no transportation of spent fuel off site and (*b*) transportation of spent fuel off site beginning in 2005. For the case of transport beginning in 2005 (the earliest conceivable year in which an interim-storage facility could open, given that it is 2001 now), for a given year, I calculated the amount of spent fuel owned by the owner-operator, subtracted the amount to be transported for that year (according to DOE schedules), and compared the result with the total capacity of storage pools at the operator-owned reactors, leaving full-core off-load space in the pool. The analysis presented in Figure 4 assumes that spent fuel is transferred between reactors within an owner-operator (although this can be complicated by public opposition; see Section 6.5). Figure 4 indicates that by 2005, almost two thirds of US nuclear owner-operators will face the need to supply on-site dry storage—even if shipments begin in 2005. Shipments beginning in 2005 would save only one owner-operator from buying on-site dry storage by the year 2007 (Figure 4). By 2010, transporting spent fuel off site would save four owner-operators (6% of all owner-operators) from buying on-site dry storage. Any delay in transportation would increase the number of owner-operators that needed to buy dry storage—for instance, if transport of spent fuel begins in 2007, almost 75% of owner-operators will be required to buy dry storage to deal with spent-fuel storage on site at some of their reactors.

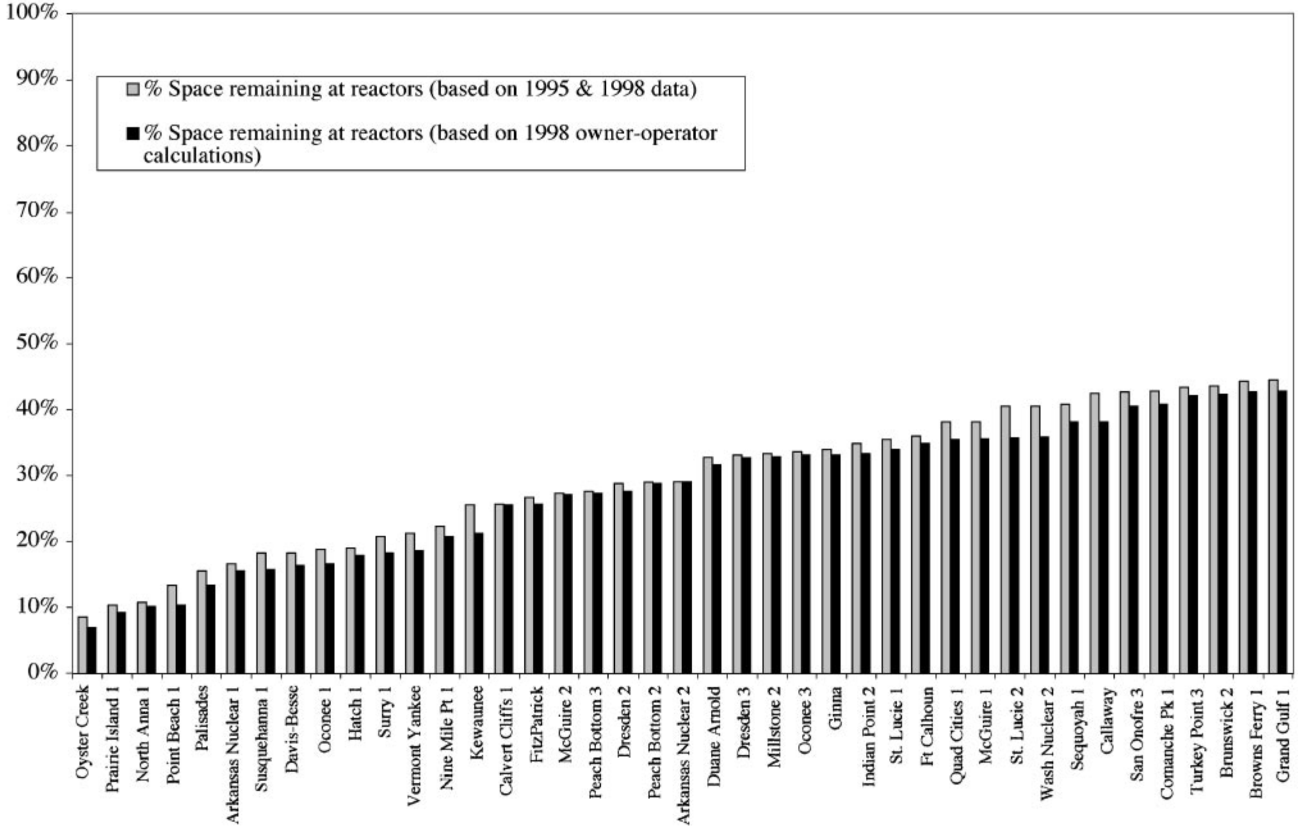


Figure 2 (*Continued*)

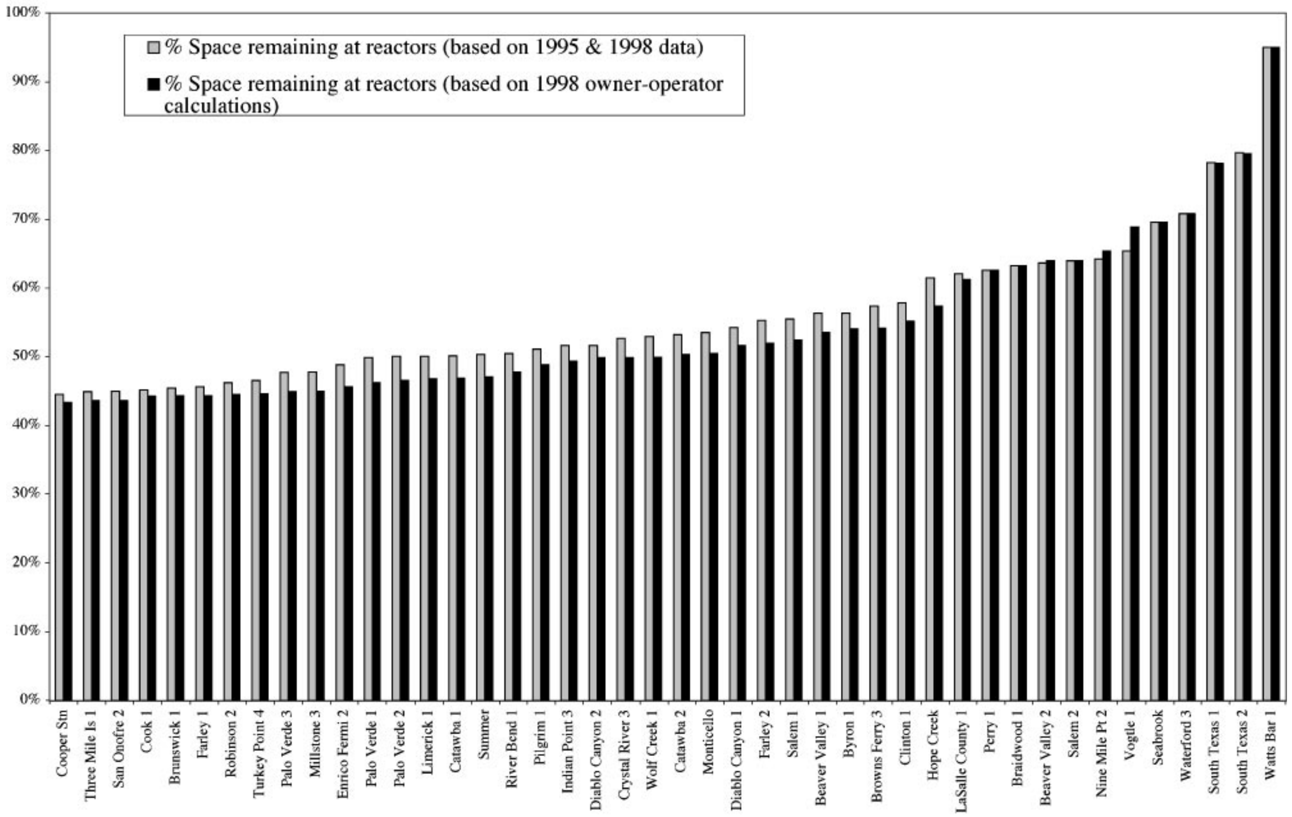
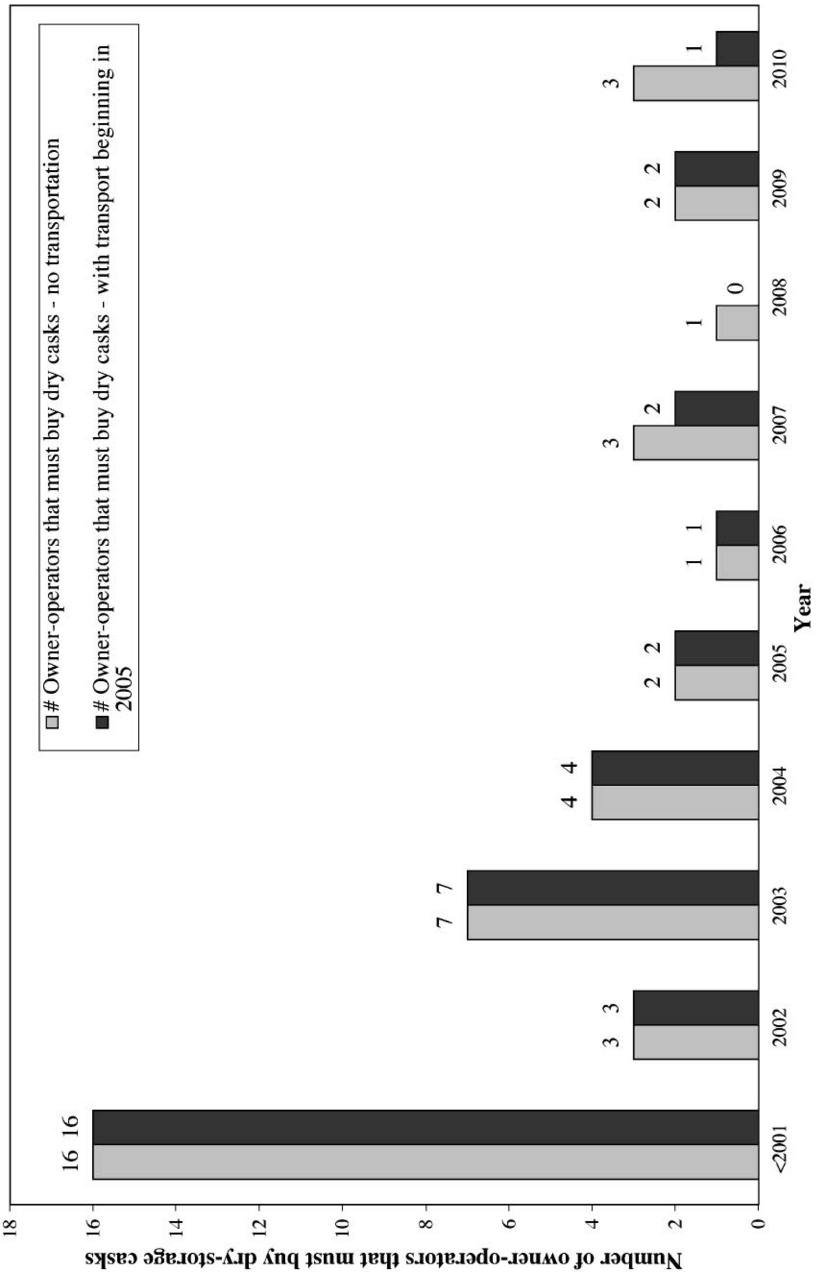


Figure 2 Plot of the percentage of space remaining in spent-fuel cooling pools at individual reactors in the United States. Two estimates are given: Those based on my calculations using 1994 and 1995 Department of Energy data [Energy Information Administration (1996), Table 10 (42), and Energy Information Administration, unpublished data, Table 10 with 1995 data included] and those given by owner-operators to the Nuclear Regulatory Commission (1998). The majority of reactors have 41%–50% of the space in their spent-fuel cooling pools open.


Number of owner-operators that must buy dry-storage casks
0
2
4
6
8
10
12
14
16
18
Year
<2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
16 16
3 3
7 7
4 4
2 2
1 1
3 2
1 0
2 2
3 1
▨ # Owner-operators that must buy dry casks - no transportation
■ # Owner-operators that must buy dry casks - with transport beginning in 2005

6. ISSUES AFFECTING INTERIM-STORAGE DECISIONS

As the above analysis confirmed, US owner-operators will require some type of spent-fuel storage beyond their existing reactor pool storage in the near future. There are two ways to approach this need: by adding more spent-fuel storage at reactor sites (in dry casks) or by constructing a centralized storage facility (also in dry casks or large vaults). The option of creating new wet-storage facilities at or away from reactors would likely be prohibitively expensive to build and operate. Deciding which of the two approaches to use should be based on a number of criteria, including which option provides better safety and security, the effects and implications of spent-fuel transportation, which approach is politically and managerially feasible, which option is more cost-effective, and whether specific considerations at a particular storage site could overly delay an option. The following discussion focuses on issues surrounding dry storage of spent fuel at reactor sites and at a potential centralized facility and addresses each of the above criteria in turn.

6.1. Safety

Dry storage of spent fuel in the United States has a good safety record. Since storage began in 1985, no major safety incidents with radiation release have occurred. The 1990 NRC Waste Confidence Decision Review (46) asserted that spent fuel is safe at reactors, in either cooling pools or dry-storage systems, for at least 30 years beyond the reactor's licensed life of operation. Furthermore, the NRC went on to say that dry storage in particular is "safe and environmentally acceptable for a period of 100 years" (46, p. 38482). Although dry storage of spent fuel is considered relatively safe and straightforward, continuing problems with dry-cask storage serve as a reminder of potential safety issues.

A few recent events have highlighted the fact that dry-storage systems need to be carefully licensed and closely monitored. In 1999, the Trojan reactor site in Oregon began to load spent fuel into Sierra Nuclear Corporation's TRANSTOR dry-storage modules only to find that the zinc-carbon coating on the carbon steel basket, intended to provide protection against the borated water of the cooling

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Figure 4 Plot showing the effect of different transportation schemes on the need for dry-storage capacity at reactors within owner-operators. In the models used in this plot, spent fuel is transported from owner-operators (not individual reactors) according to the schedule outlined by the Department of Energy (77). Categories of transportation are No Transportation and Transportation beginning in 2005, the earliest conceivable date to begin transport of spent fuel off reactor sites. By the year 2005 already 32 owner-operators will require dry-cask storage for their spent fuel. By the year 2010, transportation of spent fuel away from reactor sites will save four owner-operators from buying dry-cask storage for their spent fuel.

pool, generated hydrogen, which can cause an explosion (27, 30, 47). Similar events occurred at both Michigan's Palisades and Wisconsin's Point Beach reactors, when hydrogen generated from the Sierra Nuclear Corporation's VSC-24 basket coating caused a "hydrogen ignition event," or explosion, when the cask was welded closed (27). During the Point Beach event, the explosion lifted the 3000-kg cask lid and displaced it (30). Defective welds and cracked seals were detected in casks at Michigan's Palisades reactor and the Arkansas One reactor (48, 49). Again, these casks were of the VSC-24 design by the Sierra Nuclear Corporation. The NRC has identified some of the sources of these problems, which include poor cask-vendor oversight of subcontractors and failure of vendors (*a*) to perform quality assessment during the design process, (*b*) to follow regulatory processes during cask fabrication, and (*c*) to document repairs to casks (47, 50).

Other potential safety issues for dry storage are (*a*) whether the casks will maintain their integrity after their 20-year licensed lifetimes, (*b*) whether the current cask designs can handle spent fuel with burnups higher than 45,000 megawatt-days (MWd)/MT (27), and (*c*) how to find spare storage space if a shutdown reactor has transferred all its spent fuel to dry storage and needs to transfer spent fuel out of a leaking cask (38). The NRC is just beginning to consider the first two issues (27). None of these issues threatens the viability of dry-cask storage as an interim solution to the spent-fuel storage problem, but they do highlight the need for both continued vigilance by the regulators over both cask manufacturers and reactor operators and monitoring of cask performance during their use.

6.2. Security

A problem unique to the nuclear energy industry is the connection between nuclear energy and nuclear weapons. Spent light-water reactor fuel contains plutonium and uranium-235, fissile materials used to power nuclear weapons. In addition, the fission products and higher actinides contained in spent fuel are highly toxic and could contaminate humans and the environment if released. Because of this, spent fuel must be adequately protected against theft and sabotage.

One of the principal arguments for a centralized interim-storage facility is based on the notion that a single facility will provide a much higher level of physical security against sabotage or theft than the many nuclear reactors in which the spent fuel currently resides (e.g., 51). Although this may be true in the abstract (it is certainly easier to guard one facility than many), in actual practice it is not likely to be so. First, there is no evidence to suggest that spent fuel currently stored at reactors poses any unacknowledged security threat for which reactors are not already prepared: After all, none has ever been sabotaged or robbed, and all reactors and storage facilities are required to use physical protection measures according to NRC regulation 10 CFR 73.51, which includes two barriers, constant monitoring, and an identification and lock system. Second, a centralized site would not actually put all the spent fuel in one place. It would simply add one more place to the list of spent-fuel locations, because reactors that continue to operate will continue to have spent fuel on site.

The most obvious problem with the argument that a centralized facility is more secure is the fact that all spent fuel would have to be transported—with literally thousands of shipments. For those concerned about security, that translates into thousands of opportunities for attacks or thefts of spent fuel. In actuality, spent fuel will be at much higher risk for sabotage or theft on the roadways than at reactors. Reactors are relatively well-guarded and well-monitored places, whereas spent fuel in a moving vehicle with one or two escorts presents a more plausible security risk. NRC regulations (10 CFR 73.37) require that in populated regions, spent-fuel transports have two escorts: one in the shipping truck and one, who is armed, in an additional car. In unpopulated areas, however, no armed escort is necessary. Rail shipments of spent fuel through populated areas also require two armed escorts, although in unpopluated areas, only one unarmed escort is necessary. Both rail and truck shipments require a communications center that continuously monitors the transports, and all truck shipments require equipment that can be used to immobilize the vehicle. Nonetheless, neither of these types of shipments will be protected to the degree that nuclear weapons are under DOE and Department of Defense guidelines (52, 53).

Only a few studies have considered the effects of sabotage on nuclear spent fuel (54–56). Some reports have presented conflicting findings on sabotage. Although the DOE claimed that an attack could release only 34 g of respirable irradiated fuel, a State of Nevada report asserted that eight acres would be contaminated for every 2,000–10,000 Ci released (54, 56). Little information is available on the potential theft of spent fuel, although one DOE report suggests that a dry-storage cask could be breached by a small team of well-trained and -equipped people in 10 or 20 min (52). Dry-storage casks are clearly more vulnerable if stored outside on concrete pads (but within the fence of the reactor or centralized storage site) instead of within a reinforced concrete building, which would add additional protection against attack. Of course, it is not clear that spent fuel is more attractive to saboteurs than, for instance, federal office buildings.

6.3. Transportation

The transportation of spent fuel will be an important factor in the use of away-from-reactor storage facilities. Worldwide, the nuclear industry has transported over 88,000 MT of spent fuel in over 40,000 casks over the past 40 years (30). In the United States, over 2200 MT of spent fuel have been shipped to away-from-reactor storage sites (30). For any large-scale transport of spent fuel to a centralized storage facility (or a permanent one, for that matter), a number of issues must first be resolved, including transportation canister design, transport organization and management structure, political opposition (see Section 6.5), safety and security concerns (see Section 6.2), and cost (see Section 6.4).

In the United States, to be cost-effective, the DOE's original plan was to design a multipurpose canister that would hold spent fuel for storage, transport, and final disposal. The Office of Civilian Radioactive Waste Management in the DOE suspended work on such a design in 1996, and the design work was picked up by contractors. Currently, no multipurpose canister design has been approved because the DOE has yet to issue disposal criteria for the permanent repository. Most vendors are working on canister designs that have a single inner container that can be moved between different outer containers, such as storage containers, transport containers, and disposal containers (N. Mote, personal communication). Shipment of spent fuel is further complicated because there is no standard size of reactor fuel, so no standard size of canister will be practicable, making it impossible to take advantage of economies of scale. Only one vendor has received an NRC license for a dual-purpose canister (the NAC-STC cask), one that can be used for storage and transport, but other vendors have submitted licenses for their own designs (N. Mote, personal communication).

A more serious obstacle to large-scale transportation of spent fuel in the United States is the organization and management of it. As matters are currently structured under federal law, 10 federal agencies and numerous state, tribal, and local governments would be involved (57). For the transport of spent fuel to a permanent repository, the proposed Yucca Mountain site in Nevada, the DOE is charged with managing the transportation process and will take title to the spent fuel just before it leaves the reactor sites, but it will not have direct control over the spent fuel as it makes its way to Yucca Mountain (58). The Department of Transportation and the NRC will regulate the shipments. The Department of Transportation must ensure the safety of hazardous materials transport, whereas the NRC will license the packaging of the materials (57). Other federal agencies involved in transportation are the Federal Emergency Management Agency, the National Response Team, the Nuclear Waste Technical Review Board, the Occupational Health and Safety Administration, the Environmental Protection Agency, the Federal Railroad Administration, and the Research and Special Programs Administration. The situation is further complicated when material is transported across state and tribal boundaries because states and tribes also have some control over such shipments (57). In the past, states have designated transportation routes, regulated the hours of transport, and required licenses, permits, or fees for transport of hazardous materials (57, 59). In many cases, conflicts between federal and state, tribal, or local rules exist and must be settled in the courts (57, 59).

Although the public is fearful of spent-fuel transport on their roads and railways (see Section 6.5), over the past 40 years, no major accidents that released radiation have occurred in the United States or elsewhere. Of the 70 incidents since 1949 involving spent-fuel shipments, 13 involved actual transportation accidents, some in which loaded casks were damaged, but no radiation release was detected (60). In the United States, NRC regulations (10 CFR 71) require all transport casks to be drop tested, fire tested, and immersion tested. The NRC is currently reviewing its method for assessing these standards in response to public criticisms.

To date, the major safety problems have to do with "leaking" transport containers that result in contamination of casks, trucks, pads, and roadways. In 1998, radiation contamination was detected in French transports of empty German waste containers at levels 200 times above authorized levels (61–63). Similarly, in a number of civilian and military shipments in the United States, spent-fuel casks arrived contaminated at levels higher than allowed by the Department of Transportation (64). Since 1949, there have been 4 cases where radioactive contamination went beyond the transport vehicle, 4 cases where the transport vehicle itself was contaminated, and 49 cases where surface contamination was detected (60). In this case, the radiation leakage occurred through mechanisms, not fully understood, that involve the interaction of an oxide film on the cask surface, which incorporates radionuclides from pool water during cask loading. At some point during transport, these radionuclides migrate to the outer layer of the oxide film and create detectable levels of contamination (64).

6.4. Economics

An important factor to the owner-operator companies, the government, and taxpayers in the interim-storage debate is economics. Owner-operator companies have claimed that the DOE's missed deadline for shipping spent fuel to a permanent repository (January 31, 1998) will cost them upward of $56 billion in additional storage costs, including the addition of credit card interest rates to estimates of total owner-operator costs and refund of all past fees (65). Because of the potentially huge amounts of money at stake, it is in the interest of all involved to have an accurate accounting of the costs of interim storage of spent fuel.

For the purposes of example, this paper presents a comparison of the costs for a centralized facility at Yucca Mountain, Nevada, versus spent-fuel storage at reactor sites. The analysis also accounts for costs associated with transportation of spent fuel to the interim site, which would not accrue from at-reactor storage (at least until a permanent storage site was ready). Table 1 shows some of the costs and their sources used in the economic analysis in this paper.

Capital costs for dry storage at reactors involve (*a*) up-front costs, which include costs for design, engineering, NRC licensing, equipment, construction of initial storage pads, security systems, and startup testing (66), and (*b*) storage system and loading costs, which include costs for storage casks, additional pads, labor, decommissioning, and consumables (67). Net operating costs for at-reactor dry storage are divided into those at sites with operating reactors and those at sites with shutdown reactors. Operating costs at shutdown reactors will be higher than those at operating reactors because costs can no longer be charged against the operating reactor and instead all costs will have to be charged to spent-fuel storage. In addition, operating costs will vary depending on the number of shutdown reactors and pools at a particular site. Table 2 shows the operating costs for pools at shutdown reactors given the number of reactors at a site, the number of pools at the site, and the number of shutdown reactors. For

TABLE 1 Cost categories and sources for dry storage cost calculations in 1998 dollars

Cost category	**Capital costs**		**Operations & maintenance**	
	Up-front costs	Storage system & loading[a]	Operating reactor costs	Shutdown reactor costs
At-reactor dry storage	$9 M/site[b]	$60,000[c]–$80,000[a]/MTU	$470,000[d]–$750,000[a]/year/site	$4–9 M/year/site[e]
Centralized Interim facility	$680 M[f]	$60,000[c]–$80,000[a]/MTU	$127 M/year[g]	
	Nevada Transport	Civilian transport and operations		
		Mobilization & Acquisition	Waste Acceptance & Transportation, 2010–2041	
Transportation	$153–740 M[h]	$86 M[i]	$3912 M[j]	

[a] Includes storage casks, pads, labor, decommissioning, and consumables.

[b] Table E-7, TRW Environmental Safety Systems Inc., 1998.

[c] N. Mote, personal communication, and TRW, 1998, Table E-7.

[d] TRW Systems Analysis, 1993.

[e] Costs for reactors shut down at least 5 years. (TRW Environmental Safety Systems Inc., 1998.) For reactors shutdown fewer than 5 years, see Table 2.

[f] TRW, 1998, Table E-1. Costs are for construction of a canister transfer module and one waste handling building, and one additional canister transfer module.

[g] TRW, 1998, Table E-2. Operating costs are for the canister transfer module, the waste handling building, and the dry-cask storage area (an additional $4 M/year).

[h] TRW, 1998. Nevada transport is for either heavy-haul trucks or new railroads from Caliente, NV, to Yucca Mountain.

[i] TRW, 1999. Includes costs to develop transportation schedules, license and procure transportation equipment, and develop contracts with rail and truck lines for shipping. Represents 78.4% of the total transportation costs for this category, which are those to be borne by the civilian sector.

[j] TRW, 1999. Covers the costs of shipping all spent fuel at reactors to Yucca Mountain. Represents 78.4% of the total transportation costs for this category, which are those to be borne by the civilian sector.

reactors shutdown fewer than 5 years, operating costs are given in Table 2. For reactors shutdown 5 years or more, pool and dry-storage operating costs are estimated to be $9 million per year (67). For shutdown reactors with all their spent fuel in dry storage, operating costs are estimated to be $4 million per year (67).

A recent DOE report, which describes a modular interim storage and waste processing facility that would be integrated with the permanent repository facilities at Yucca Mountain, contains a description of the facilities necessary for centralized storage (67). The capital costs below are the bare minimum required for a centralized storage facility and nothing further, and they do not include costs for facilities to handle uncanistered spent fuel. Capital costs of building an independent dry-storage facility include construction of (*a*) a carrier preparation building, where loaded transportation casks would be received and prepared for, (*b*) a waste

TABLE 2 Annual costs for pool operations and maintenance at shutdown reactors in 1998 dollars[a]

Number of shutdown reactors at a site	Number of pools on site	Costs by number of reactors on site		
		1	**2**	**3**
1	1	$4,675,024	—	—
1	2	—	$738,742	$738,742
1	3	—	—	$738,742
2	1	—	$4,675,024	—
2	2	—	$5,149,142	$738,742
2	3 (1 shutdown)	—	—	$738,742
2	3 (2 shutdown)	—	—	$1,576,718
3	1	—	—	—
3	2	—	—	$5,248,376
3	3	—	—	$6,097,378

[a] For reactors shut down fewer than 5 years. For reactors shutdown 5 years or longer, if no other pools are operating, then the operating costs jump to $9 million/year. For reactors, like Trojan in Oregon, that move all their spent fuel into dry storage (instead of continuing to operate pools), once all the fuel is in dry storage, operating costs are $4 million/year. (Adapted from TRW Systems Analysis, 1993.)

handling building, where the fuel would be unloaded from the transport carrier and loaded into storage casks if necessary (67), (*c*) a canister transfer storage module, where overflow casks await processing (for the scenario in which up to 3000 MT of spent fuel is shipped per year), and (*d*) pads and concrete storage casks for the spent fuel. Decommissioning costs are included as a separate capital cost because they are not considered in DOE's analysis. Estimates for decommissioning costs (which depend somewhat on the availability of multipurpose casks; if storage casks are different from those emplaced in the permanent repository, then costs will increase because of the need to decommission the storage casks as well as the spent-fuel transfer facilities and other radioactive areas) are based on 15%–20% of the facility capital costs (66). Operating costs are a bare minimum estimate and apply to costs accrued only from operating the carrier preparation building, $44.1 million/year (without facilities for uncanistered fuel), the one waste handling building, $78.8 million/year (67), and those for the maintenance of dry-storage facilities, estimated at $4 million/year based on operating costs for an independent spent-fuel storage facility (68). All at-reactor scenarios assume that no license extensions are granted to currently operating power plants.

Although many of the interim-facility costs in this analysis originate from owner-operator industry estimates, transportation costs are based on estimates provided by DOE analyses (see Table 1 and Figure 5). Various routing options through Nevada exist and account for the variation in cost (See Section 6.6; Table 1). Costs for the transportation of all civilian spent fuel (Table 1) are estimated to be 78.4% of total transportation costs (with the remainder accounted for by spent-fuel and high-level waste from DOE and Department of Defense programs) (69). The transportation and operations cost estimate in Table 1 does not include costs for waste acceptance, storage, and transportation development and evaluation (estimated to be $36 million between 2000–2005) (69).

Figure 5 provides a comparison of costs in billions of 1998 dollars of on-site, at-reactor dry-storage versus centralized dry-storage costs versus transportation costs, projected out to the future for the years 2010, 2015, 2025, or 2041.[2] All costs are discounted at a 5% rate, based on government interest rate projections. At-reactor costs to owner-operators are calculated for storage of spent fuel on site up to the year of the particular case (2010, 2015, 2025, or 2041). Centralized storage costs to the DOE are calculated for a centralized facility that is completed and begins to accept spent fuel by 2005, according to the DOE's transportation schedule.[3] For example, in the year 2010, the costs would be based on the amount of spent fuel received at the centralized facility between 2005 and 2010. Transportation costs in this figure are calculated by discounting the per-year costs (see 68) from 1998 to 2010, 2015, 2025, or 2041, depending on the case, and adding them together over the specified time period (68).

Costs for transportation are calculated using year-by-year cost estimates (68). Added to these costs are the mobilization and acquisition costs of $86 million, discounted to a 2005 pay date. These costs cover establishing schedule agreements with each reactor site for the removal of spent fuel, acquiring and licensing transportation equipment, and establishing contracts for transportation shipments (68).

Figure 5 shows that transportation costs are between 40% and 50% of those for a centralized facility. As a result, transportation costs will add significantly to the total costs for a centralized interim-storage facility depending on where it is constructed (Figure 6). For a facility at Yucca Mountain, these costs, of course, will be recouped if a permanent repository opens there, except for discounting. On the other hand, if Yucca Mountain is not approved as a permanent geologic repository, or if it is aborted in 10–30 years, then the loss to the taxpayer is on the order of billions of dollars.

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[2] All cases are calculated with 1998 as the initial year because costs are in 1998 dollars. Assuming no license extensions at reactors, between 1998 and 2010, only five reactors will shutdown. Between 2010 and 2015, 36 reactors will shutdown, and between 2015 and 2025, 37 reactors will close. According to the model employed in this paper, all reactors are shutdown by 2041.

[3] The DOE plans to transport 400 MTU of spent fuel in the first year transportation begins, 600 MTU in the second year, 1200 MTU in the third year, 2000 MTU in the fourth year, and 3000 MTU each year thereafter (68).

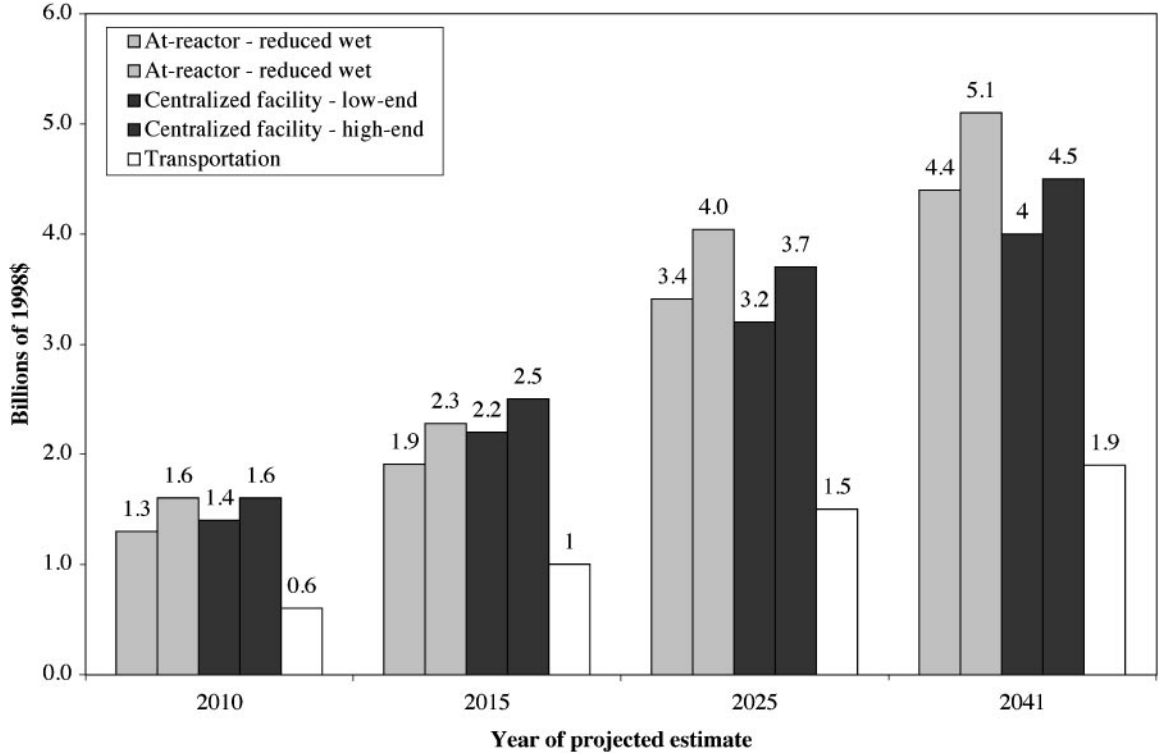

Figure 5 Cost comparison for capital, operating and maintenance, and transportation costs for interim storage of spent fuel for the years 2010, 2015, 2025, and 2041. (*Light gray boxes*) At-reactor storage, high and low estimates; (*dark gray boxes*) centralized facility storage; and (*white boxes*) transportation costs accrued for centralized facility storage. All costs are in 1998 dollars. See text for details.

If we disregard the complexities added by transportation and just compare capital, decommissioning, and operating costs for at-reactor and centralized storage, we see that there is little difference between the two total costs (Figure 5). An estimate of the uncertainty associated with these figures is at least 10%, if not higher. All of the total cost estimates, high and low, at-reactor and centralized, for a particular case, 2010, 2015, 2025, or 2041, fall within a 10% error range of each other. What does vary between at-reactor and centralized costs and across the cases are the capital and operating costs. For the at-reactor case, if spent fuel is not transferred from wet to dry storage at shutdown reactors, then operating costs dominate. As a result, the data shown in this paper assume that all spent fuel in the at-reactor case is transferred to dry storage after the reactor is shut down. For the centralized-facility case, in the year 2010, the costs are fairly evenly divided between the storage-system, up-front, and operating costs, but by the year 2015, storage system capital costs dominate.

Two other observations are possible. The first is that up-front costs are consistently higher for centralized storage than for at-reactor storage. A centralized facility will require, at the minimum, a carrier preparation building, where workers remove the personnel barriers from the waste carriers (on truck or rail car) and the impact limiters and inspect the carrier for contamination (70), and a waste handling building, where casks are removed from the carrier, both carrier and casks are decontaminated, and the cask is opened to reveal the inner canister of spent fuel, which can be repaired if necessary. The waste handling building will need at least one pool in the event of failed casks, failed spent-fuel assemblies, or earthquake damage (70). In fact, the analysis here most likely underestimates the up-front costs for centralized storage by accounting for only two initial waste buildings. Actual up-front costs may be a few hundred million dollars higher.

The second observation is that by 2041, operating costs for the at-reactor case are 44% higher than those for the centralized facility case. Centralized storage of spent fuel, then, becomes more cost-effective only if spent fuel is to be stored for at least five decades before a permanent repository is available. High transportation costs offset these savings, though. A centralized facility will become economically viable when transportation costs are reduced. This cost reduction can be accomplished by reducing transport distances by siting a centralized facility closer to reactors. Costs could also be reduced by the introduction of a multipurpose cask that could be used for final disposal as well as interim storage and transport. The decision on what type of cask is needed for a permanent repository at Yucca Mountain does not appear to be forthcoming for at least five years.

6.5. Politics

Interim storage of spent fuel may be technically safe and cost-effective, yet political opposition may obstruct storage plans, ultimately causing nuclear reactors to shut down from lack of storage space. Consequently, public concerns are an issue that should be given weight equal to those discussed previously. Political opposition

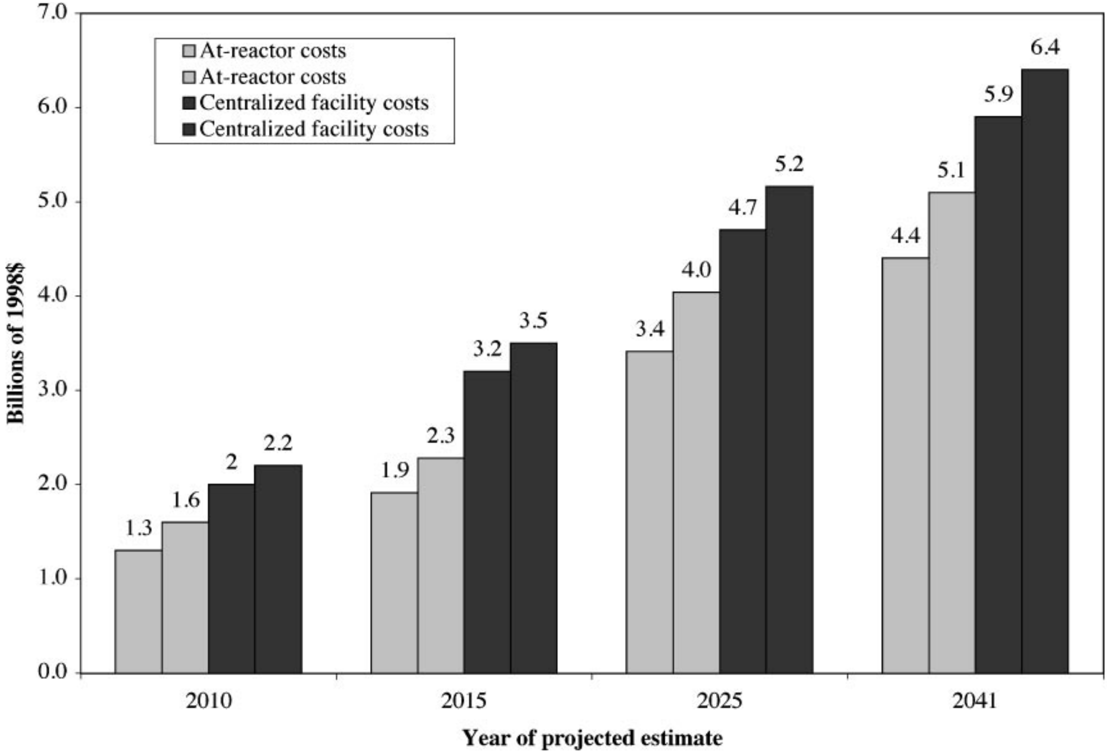

Figure 6 Cost comparison of at-reactor and centralized storage of spent fuel for the years 2010, 2015, 2025, and 2041. Transportation costs are included in the centralized cost estimates. (*Light gray boxes*) At-reactor storage, high and low estimates; (*dark gray boxes*) centralized facility storage. All costs are in billions of 1998 dollars.

to interim storage of spent fuel takes two main forms: (*a*) the not-in-my-backyard syndrome against actual spent-fuel storage facilities—either at reactors or at a centralized interim-storage facility—and (*b*) opposition to the transport of spent fuel.

A few reactors may be shut down if no off-site storage space is available for use because the local public refuses to approve more on-site storage. Northern States Power Company in Minnesota has been bound by the state legislature to make progress finding away-from-reactor storage before the state will approve additional dry-cask storage (71). In addition, Wisconsin's public service commission has allowed only 12 dry casks at the Point Beach reactor—and may not allow more until the spent-fuel problem is addressed by the federal government (71). Although both these events caused the nuclear industry major concern, neither resulted in the shutdown of the reactors—although this may occur in the future.

Political opposition to proposed centralized facilities also exists. The state of Nevada strongly opposed a centralized interim-storage facility near Yucca Mountain on the grounds that it was being doubly "penalized" by siting not only a permanent repository but also an interim facility there. As a result, the state of Nevada would try to delay the opening of any storage facility as long as possible through lawsuits and other means. Moreover, many Nevada localities, including Las Vegas, may prohibit or at least highly restrict transport of spent fuel on their roads. Further political barriers to a centralized facility at Yucca Mountain would be public protests, such as those against the permanent repository, which is on ground claimed to be sacred by the Western Shoshone and the Southern Paiute Indians. The Clinton Administration also opposed interim storage at this site because it could influence the decision on the location for a permanent repository. The state of Utah has responded like Nevada by opposing the creation of a private interim-storage facility on Goshute Indian land near Salt Lake City because of concerns over safety and earning the reputation of a "waste dump." It is very likely that almost any centralized storage facility in the United States will also face some kind of lawsuit. For example, in the case of Utah, it will most likely be brought by the state and challenge the sovereignty of an Indian nation.

Besides the not-in-my-backyard response, the public is wary of transportation of radioactive materials through their communities and on their roadways. The antinuclear community's response to congressional proposals to create an interim-storage facility near Yucca Mountain was their (somewhat misleadingly named) "mobile Chernobyl" campaign against the transport of spent fuel in which they highlighted alleged dangers of spent-fuel transportation. Germany presents perhaps the most spectacular example of the power of public protests against spent-fuel shipments: Over 30,000 police were called out to defend against thousands impeding the transport of spent fuel to the Gorleben interim-storage facility in 1997 (72). The above suggests that in any planned transportation of large amounts of spent fuel, the transporters will first have to work hard to gain the public's trust for the operation to be successful.

6.6. Site-Specific Considerations

To create a centralized interim-storage facility for spent fuel, policymakers have to account for the factors discussed in the previous sections, but each specific location will have its own unique issues that require resolution. Congressional legislation between 1995 and 1999 that addressed interim storage of spent fuel specified that a valley within the Nevada Test Site, Jackass Flats, located within 10 km of Yucca Mountain, be used for a centralized facility. Jackass Flats, therefore, provides a good example of specific additional considerations that arise once a site is chosen.

One issue that a facility near Yucca Mountain would encounter has to do with spent-fuel shipments. The transportation of spent fuel from reactors to a centralized interim-storage site near Yucca Mountain would be no small task. The vast majority of nuclear power plants are in the east or midwest, and as a result, great distances would be traveled over the thousands of trips that would need to be made (Figure 1). A large chunk of capital costs will be invested in the transportation system within Nevada because there is no direct route (rail or road) from the end of the rail line in Caliente, Nevada, to the proposed storage facility at Jackass Flats adjacent to Yucca Mountain. Caliente is located approximately 150 miles north of Las Vegas (which is about 90 miles southeast of Yucca Mountain). As the crow flies, Caliente is approximately 100 miles from Yucca Mountain. Originally, the plan was to extend a rail line from the town of Caliente to Jackass Flats. Another option is to forego the more expensive but potentially safer rail line and use heavy-haul truck transport from Caliente through Las Vegas to Jackass Flats. In this case, a facility for the transfer of spent fuel from large rail casks to smaller truck casks would be required, in addition to improvements of various roadways to accommodate the increased weight of the trucks. The DOE pointed out that heavy-haul truck transport may become untenable if the state of Nevada refuses to provide the necessary permits, in which case a rail line would need to be constructed (67).

Another issue particular to a storage site at Yucca Mountain is seismicity. (This issue also applies to individual reactor sites that are seismically active and, because of that, cannot use their general license for dry storage.) Yucca Mountain is located within the Basin and Range tectonic province of continental North America, an area generally known for its mountains, desert valleys, and seismic activity. The area within the Nevada Test Site boundaries has experienced numerous small earthquakes over the past years, excluding those caused by nuclear weapons tests (Figure 7). In 1992, the Yucca Mountain area experienced a magnitude 5.6 earthquake centered on a previously unknown fault at Little Skull Mountain, situated about 10 km from Jackass Flats (Figure 8). The earthquake resulted in over 2000 aftershocks, and some of the already-existing facilities on Jackass Flats were damaged (P. Justus, personal communication).

Earthquake damage depends on a number of factors, such as the intensity of the earthquake (the actual energy released during fault slippage), distance from the epicenter of the earthquake, duration of the earthquake, ground conditions at a particular location, and building and structure quality.[4] For the Jackass Flats region, ground motion is one of the more salient factors in predicting damage to structures. Jackass Flats is actually a basin filled with about 100–300 m of unconsolidated boulder- to silt-size sediment (73) that experiences higher ground motions relative to the surrounding areas because sediment is less rigid than the surrounding bedrock (74). For example, in January 1999, a swarm of small earthquakes produced ground motions at Jackass Flats on the order of 0.0033 g, which were the highest ground motions experienced in the area (P. Justus, personal communication). Similar situations exist in Kobe, Japan, and the Marina District of San Francisco, both of which are located relatively far from the epicenter of the earthquakes that produced the wreckage but which experienced much higher damage than would have been expected because of the unconsolidated sediments on which they are located.

The NRC has the authority to decide whether to grant a license for the construction of an interim facility. Part of NRC's analysis for license approval will be based on regulations regarding the siting of an independent storage facility in a seismically active area (10 CFR§72.102). These regulations state that "sites other than bedrock sites must be evaluated for their liquefaction potential or other soil instability due to vibratory ground motion" [10 CFR§72.102 (c)]. The real question to be answered for NRC license approval is whether any facilities are planned that will require the removal of spent fuel from its inner canister in a pool of water by a crane. If so, license requirements will be more stringent because the seismic hazards are greater from the potential for radioactivity release. Such facilities are most susceptible to earthquake damage, especially if a load of spent fuel is dangling from the crane when an earthquake hits. While a facility at this location would presumably be designed to withstand plausible earthquakes, there would inevitably be added complexities, costs, and risks compared with building the facility at a less seismically active site.

7. CONCLUSIONS

In the United States, what is the fate of spent fuel? Because a permanent repository will not be available before the year 2010 at the earliest, it is clear that additional storage will be needed, most likely dry storage. The question is whether that storage will be located at reactor sites or in a centralized facility. Technically, either option is viable, as long as there is adequate attention paid to safety issues. The economic analysis of the options presented here suggest that at-reactor storage

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[4] Earthquakes are much more of an issue for surface facilities than for underground facilities (like the proposed repository). The situation is similar to that of a ship and a submarine at sea during a storm: The ship will be much more affected by the intensity of the storm than will the submarine, which is not affected by surface waves.

is most cost-effective, but owner-operator companies may decide that the higher costs are worth the political payoff of moving the spent fuel off site. At odds with this is political opposition to both a centralized facility and the transportation of spent fuel, which would, at the very least, serve to delay the acceptance of spent fuel at a centralized site. Perhaps there is some middle ground similar to that advised by the MRC Commission a decade ago: Establish a small-volume centralized facility that would take spent fuel from only those reactors threatened with shutdown if they cannot move their fuel off site. This facility would need to be sited in an accepting community.

In the 1980s there was, in fact, a proposal to site an interim-storage facility in the United States in a locale that was supportive of such a facility: Oak Ridge, Tennessee, home of the Oak Ridge National Laboratory, which produced uranium for nuclear weapons. Because of its central location relative to the majority of the nation's nuclear reactors, the DOE planned to create a facility that would repackage and store spent-fuel rods prior to sending them to a permanent repository (75). Although the state government tried to block the plan with a lawsuit against the DOE, a local Oak Ridge, Tennessee, county commission agreed to an interim-storage site in exchange for certain guarantees and benefits (38, 76). In the end, the state was successful in preventing the construction of the facility. Perhaps it is time to reconsider an offer like that of Oak Ridge. Potential alternative sites would be something like the Morris site in Illinois or the Fort St. Vrain site in Colorado. Although the wet and dry storage at these sites are filled almost to capacity and they are not currently licensed for more, they could be potential locations for a small dry-storage facility because they already have spent fuel on site.

In the end, the debate about the interim storage of spent fuel hangs on the future of nuclear energy. If fossil fuels become a pariah energy form due to global climate change and nuclear energy experiences a revival, or if, on the other hand, the country decides nuclear energy has come to the end of its usefulness (such as the recent decision in Germany), then the political will to oppose a solution to a problem that clearly requires one may abate. On the other hand, if the public sees no solution to the nuclear waste problem and continues to perceive that owner-operator companies and the federal government are not to be trusted with dangerous radioactive materials, then most likely no centralized facility will be successfully established and some reactors will shut down from lack of storage space. The solution to the problem relies on a number of factors, not the least of which is public opinion—and positive public opinion must be earned.

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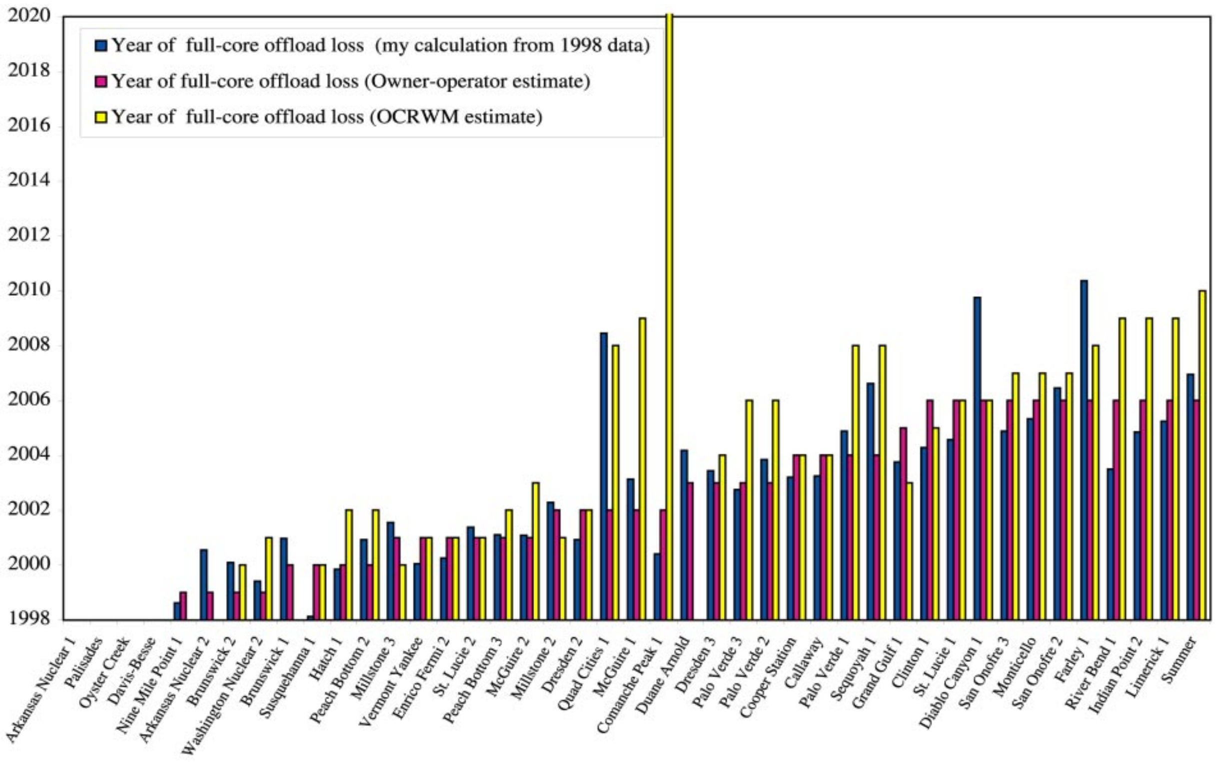

Figure 3*a* Plot of year of loss of full-core off-load by individual reactor. Year of core off-load loss indicates the time at which reactors will no longer be able to function unless they solve their spent fuel storage problem, either by adding dry fuel storage or by removing the waste from the reactor site. Three models are used to calculate year of full-core off-load loss. (*blue*) The model based on my calculations of space given in Figure 2; (*red*) the owner-operator's estimate (from the Nuclear Regulatory Commission); (*yellow*) the Office of Civilian and Radioactive Waste Management's (OCRWM) estimate (1995).

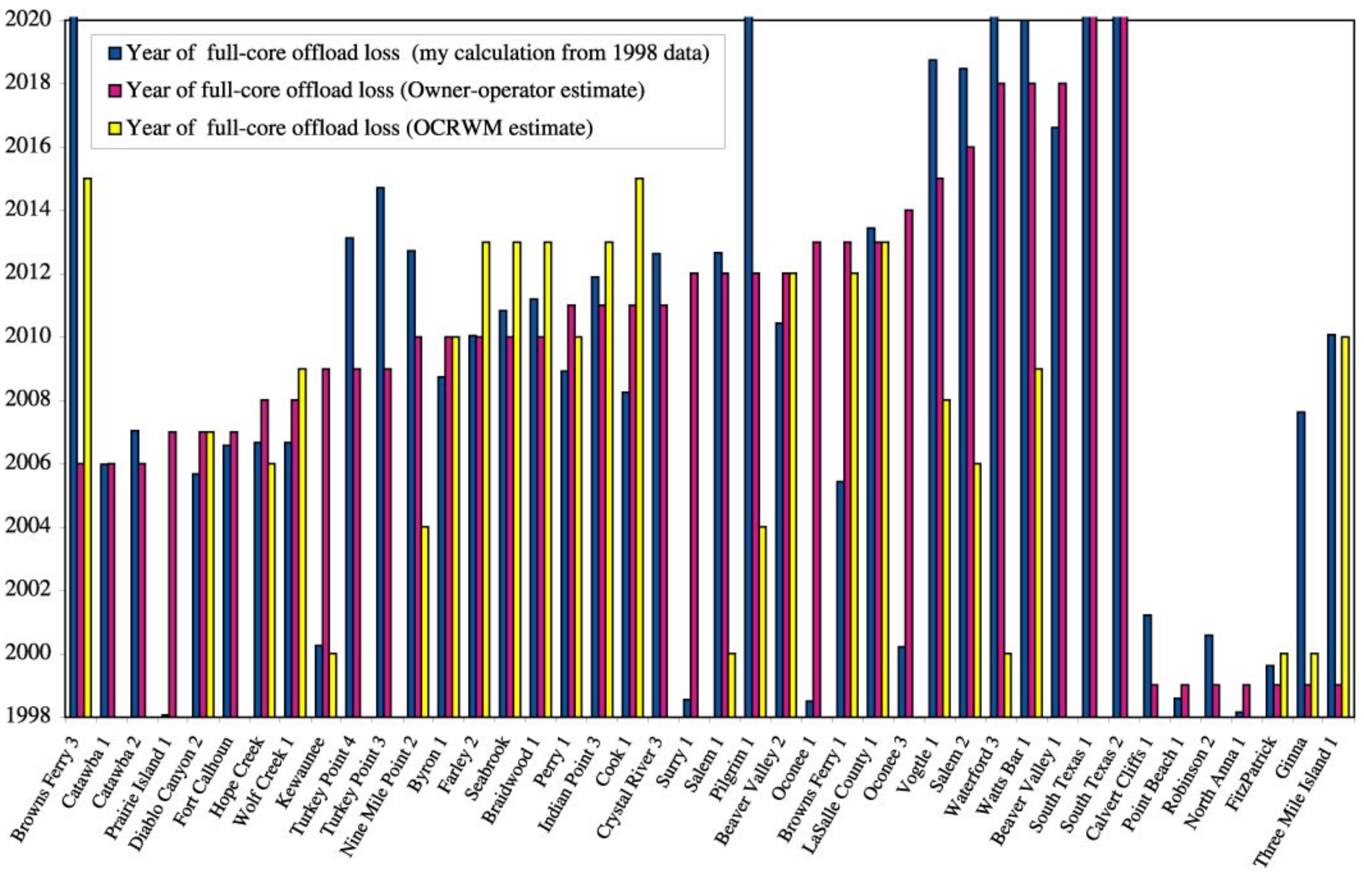

Figure 3*b* see legend on previous page C-1.

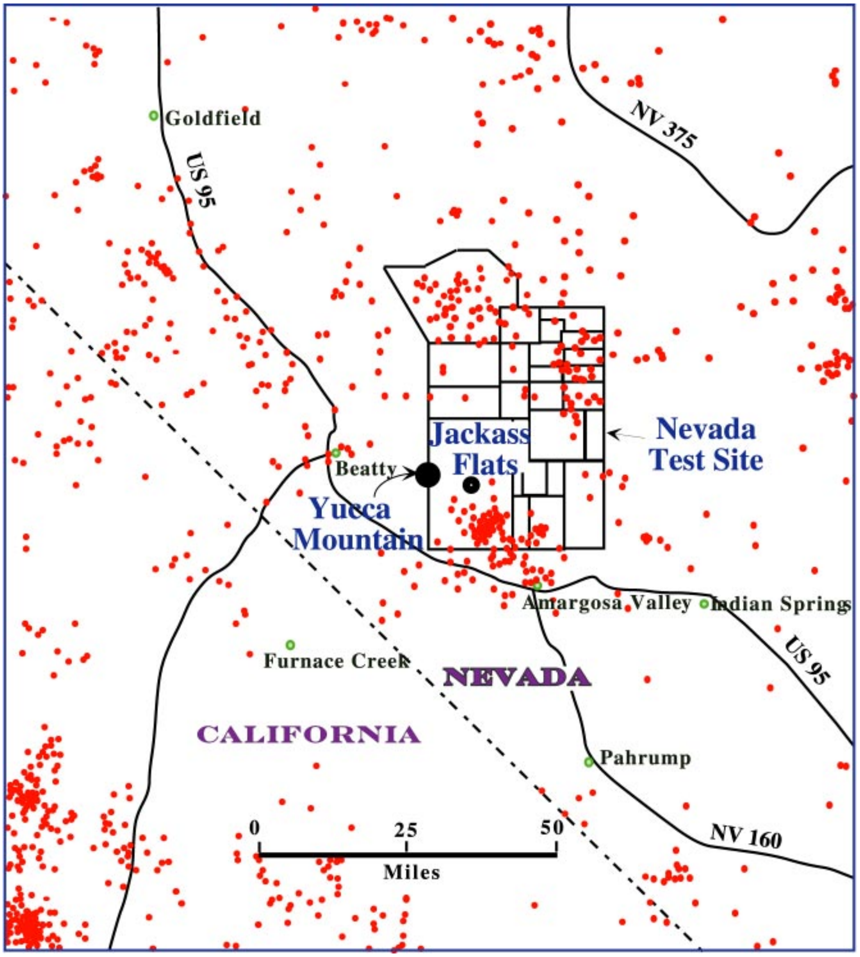

Figure 7 Locations of earthquakes (*red*) of magnitude 2.5 and greater from 1976–1996 in the region of the Nevada Test Site. The locations of Yucca Mountain and Jackass Flats are shown with “bullseye” symbols. Selected roads are shown on the map. The cluster of earthquakes just to the southeast of Jackass Flats represents the main quake and two thousand aftershocks from the 1992 Little Skull Mountain earthquake. (Adapted from Nevada Nuclear Waste Projects Office and the National Seismic System Composite Catalog.)

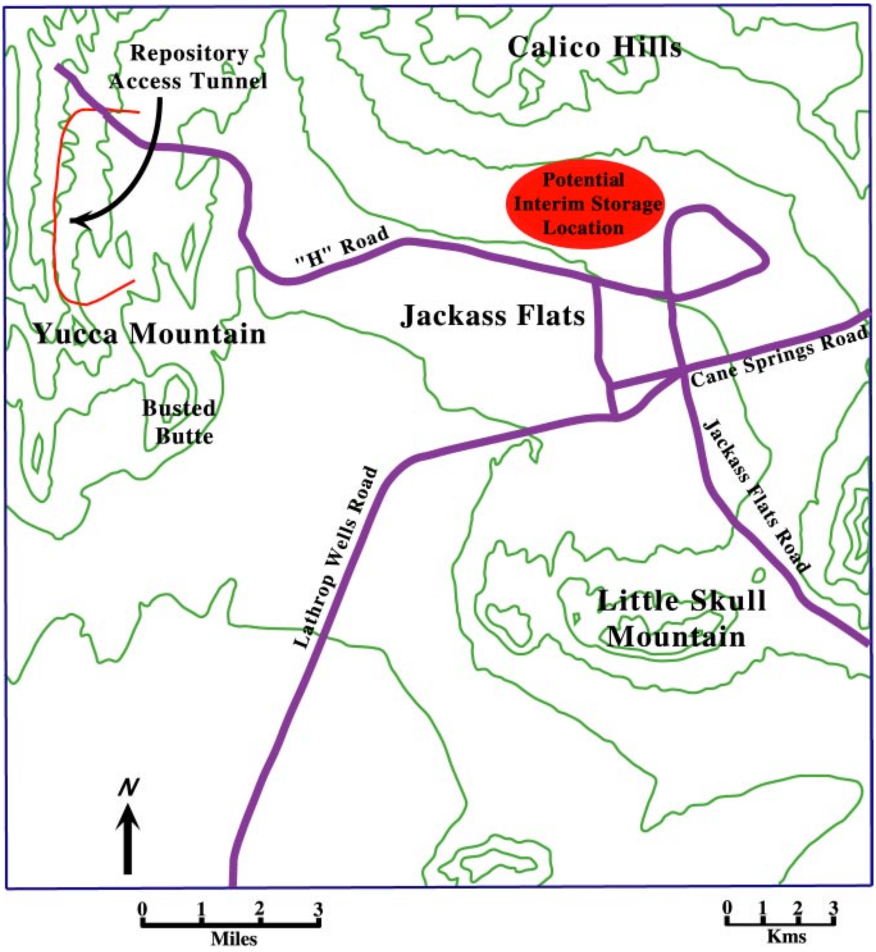

Figure 8 Topographic map of the Yucca Mountain area, Nevada. The 5-mile-long repository access tunnel (*curved red line*). The location for the potential interim storage facility (*red oval*). Also shown are Yucca Mountain, Jackass Flats, and Little Skull Mountain. (Adapted from Yucca Mountain Site Characterization Project, 1996.)