ELSEVIER

Energy Policy 29 (2001) 1379–1389

ENERGY POLICY

www.elsevier.com/locate/enpol

The problem of used nuclear fuel: lessons for interim solutions from a comparative cost analysis

Allison Macfarlane*

Security Studies Program, Massachusetts Institute of Technology, 292 Main Street, E38-620, Cambridge, MA 02139, USA

Received 8 May 2000

Abstract

An acceptable long-term solution for used (spent) fuel from nuclear power reactors has evaded all countries engaged in the civilian nuclear fuel cycle. Furthermore, many countries are trying to develop interim storage solutions that address the shortage of storage in the spent fuel cooling pools at reactors. The United States has a particularly acute problem due to its adherence to an open fuel cycle and its large number of reactors. Two main options are available to address the spent fuel problem: dry storage on-site at reactors and centralized storage at a facility away from reactors. Key to deciding which option makes better policy sense is the comparative economics of the two options. This paper provides one of the few comprehensive comparisons of costs for the two alternatives and discusses implications for other schemes and possible alternative solutions to the spent fuel problem for the United States. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Spent fuel; Nuclear energy; Energy policy

1. Introduction

Forty years of nuclear power usage has produced no permanent solution to the management and disposal of back-end waste products. Even the short-term management of spent fuel from nuclear power reactors is debated: should it be stored on site or should it be stored at a centralized facility off-site? The United States may suffer more from this problem than other countries in that it has many more nuclear power plants than most other nations and thus more spent fuel, but it is not unique in having to deal with these problems. Japan, for instance, faces a storage space shortage at their reactors and as yet has no solution to the problem. Originally, they had planned to move spent fuel off site to a reprocessing plant — but that plant remains under construction while spent fuel builds up at local reactors. Thus, the problem of how to manage spent fuel in the interim, before a permanent solution is agreed upon, is an important issue for all countries that use nuclear power.

The spent fuel storage situation in the United States is becoming increasingly urgent, and it is possible that some reactors may even be forced to shut down if this issue is not resolved. US nuclear reactors have produced over 40,000 metric tons (MT) of spent nuclear fuel, which currently resides on-site at reactors. By the end of the existing 103 currently licensed, operating reactors' lifetimes, the total amount will likely be over 80,000 MT. Still more will be generated if reactor licenses are extended, as they are beginning to be now. None of these reactors has the capacity to store all the spent fuel they will produce over their lifetimes. To relieve the burden of spent fuel storage from cooling pools at individual nuclear reactors while they await the opening of a permanent repository, they will need some type of interim solution. One option is to store the spent fuel on site in dry casks, while an alternative option would be to create a centralized interim storage facility. The US Congress recently considered establishing a centralized storage facility near Yucca Mountain, Nevada, and at least two private facilities are under review for large-scale spent fuel storage. Spent fuel storage, therefore, will remain at the top of many agendas and as a result, it is important to understand the issues involved to make the best choices possible.

One of the main debates over the best way to resolve the spent fuel problem in the short term is over the comparative cost of the options. Those who support

* Corresponding author. Tel.: + 1-617-253-0736; fax: + 1-617-258-5750.

E-mail address: allisonm@mit.edu (A. Macfarlane).

PII: S0301-4215(00)00162-2

a centralized interim storage site contend that a centralized facility for spent fuel would minimize at-reactor storage and, as a result, significantly reduce costs (Kraft, 1999). On the other hand, the transportation of spent fuel from power reactors to another location would entail additional costs not included in at-reactor storage. Why should these costs be borne now, instead of waiting until a permanent repository is actually available, thereby discounting the transport costs? The benefits of consolidated storage, moreover, may take decades to achieve. To settle this debate, a comparative analysis is required. Unfortunately, to date, neither Congress nor the Energy Department have completed a current detailed analysis of the costs of the at-reactor and centralized facility options. To address the spent fuel storage issue, this paper will provide such a cost comparison.

To make effective spent fuel policy, policy-makers should be concerned with the question of whether centralized storage would be a cost-effective measure. Other questions, such as whether centralized storage of spent fuel is politically and technically feasible are arguably as important as the economic one, but they have been dealt with in other publications (see Macfarlane, 2001). Although the case presented in this paper specifically addresses the situation in the United States, this analysis will provide a template discussion that is applicable to the situations in other countries.

The record has shown that nuclear waste issues, especially those in the United States, do not particularly lend themselves to easy solutions. For instance, currently there are no permanent operating repositories in the United States for the nation's low- or high-level wastes.[1] Costs for the interim storage of spent fuel will run into the billions of dollars. The significance of this issue can be measured by the level of frustration that already exists in the US Congress over the costs of developing a permanent nuclear waste repository at Yucca Mountain, Nevada. To avoid wasting huge sums of the taxpayers' money, it is necessary to have a good understanding of the costs involved in the interim storage of spent fuel before proceeding with any particular policy recommendation. The discussion in this paper should clarify the costs to be paid and will suggest alternative solutions to the spent fuel problem.

2. Policy background

Many utility companies that own nuclear reactors expected that the spent fuel problem would be resolved by now because US law stipulated that the Department of Energy (DOE) would begin to move it by 1998. The Nuclear Waste Policy Act (NWPA) of 1982 established that spent fuel and other high-level radioactive waste would be disposed of in a geologic repository. It also set the date to begin the transportation of spent fuel from reactors as January 31, 1998. Even though amendments to the NWPA designated a location for a repository in 1987 (Yucca Mountain, Nevada, was selected), by the early 1990 s, it was clear that such a facility, if licensed, would not be able to accept spent fuel until at least 2010. By corollary, then, it was clear that utilities would have to find some way to accommodate the spent fuel on their own.

Interim storage of spent fuel is not a new concept in US policy. The Nuclear Waste Policy Act allowed the construction of a centralized interim storage facility for spent fuel. To ensure fairness in storing and permanently disposing of nuclear waste, the NWPA prohibited the siting of a centralized storage facility in any state under consideration as a permanent repository site. The 1987 Nuclear Waste Policy Act Amendments (NWPAA) alleviated concerns that a centralized storage facility would become a defacto permanent repository by the provision that construction of a centralized facility could only occur after the license for a permanent repository was granted (Gerrard, 1994). Again, as with the NWPA, the NWPAA distinctly forbade the construction of a centralized storage facility in the state of Nevada, the designated location for a permanent repository.

A Monitored Retrievable Storage Commission, established by the NWPAA, determined that some type of interim storage would be needed, but not a large volume facility (Monitored Retrievable Storage Commission, 1989). The Commission noted that the net cost of the centralized storage facility option might be less than no centralized facility, but that the centralized storage facility option would be more costly on a discounted basis. They noted that a centralized storage facility, linked to the licensing of the permanent repository as it was in the NWPAA, would not address storage issues. The MRS Commission recommended that Congress authorize a federal emergency storage facility licensed to hold 2000 MTU of spent fuel and a utility-funded facility licensed to contain 5000 MTU (Monitored Retrievable Storage Commission, 1989), though none was ever constructed.

When it became clear to the nuclear utilities that DOE would not meet the 1998 deadline by which it was to accept their spent fuel, they began to address the problem themselves by lobbying for legislation to establish a centralized interim storage facility at Yucca Mountain and by entering into negotiations with Indian tribes and other localities to develop privately managed interim storage facilities. Three of these private storage options have received considerable attention, two on tribal lands,

[1] The Waste Isolation Pilot Project was finally allowed to receive defense complex transuranic waste years behind schedule. Furthermore, the few existing low-level sites (Barnwell, South Carolina, for example) take waste only from a limited number of states. Most states have no permanent repository for low-level waste.

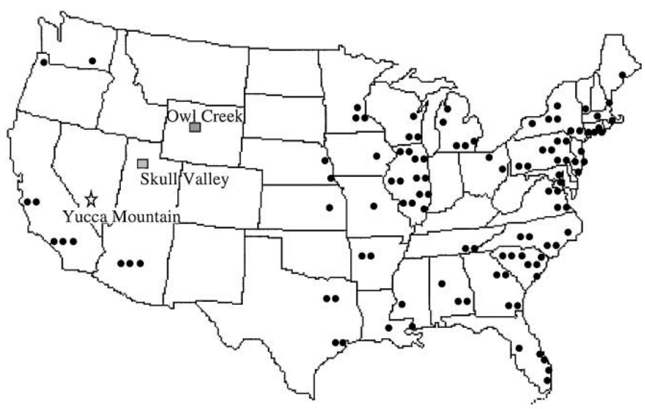

Fig. 1. Map of nuclear power reactor locations in the United States. The cross symbol indicates the location of Yucca Mountain, the proposed permanent repository site, and the proposed Owl Creek and Skull Valley private centralized storage facilities.

and one on state land.[2] Eleven utility companies led by Northern States Power joined with the Mescalero Apache tribe of southern New Mexico to attempt to establish a 10,000 MTU facility on tribal land (Carter, 1994; Dow Jones and Company, 1996). The question of whether to offer Mescalero land for an interim facility was a contentious one within the tribe. The Mescalero's first vote on the interim facility decided against it, but a second vote of questionable legitimacy decided for such a facility (Hanson, 1998). The utility companies abandoned the storage proposal in 1996, when they suspended negotiations with the tribe (Dow Jones and Company, 1996).

Perhaps the most successful private option so far is an offer from a consortium of electric power utilities and an Indian nation, the Skull Valley Band of the Goshute Indians, in Utah. Eleven utility companies signed an agreement with the tribe in 1996 to open a spent fuel storage facility on the Goshute reservation, 70 miles southwest of Salt Lake City (Fig. 1). The proposed facility would contain up to 40,000 MTU of spent fuel. The consortium, Private Fuel Storage, submitted a license application to the NRC in June, 1997 (Associated Press, 1998; Holt, 1998). If approved, the group hopes to open the facility by 2002 (Holt, 1998). Such an early date is unlikely based on the promised legal battles from the state of Utah, which objects to the proposed facility.

The Owl Creek Energy project proposed for a site near Shoshoni, Wyoming, is one of the few sites proposed on non-tribal land (Fig. 1). The Owl Creek project consortium members include 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 (Woolf, 1997). The local government in central Wyoming is tolerant of the project, and it is supported by the local state senator, Bob Peck (R-Riverton) (Bob Peck, pers. comm., 1999). The consortium plans to submit a license application to the NRC in 2000 and would like the facility to be operational by early 2004 (Ivan Stuart, NAC International, pers. comm., 1999). The future of the project remains uncertain, with the governor of Wyoming appearing to object to the facility (Black, 1999), and other state legislators such as Mike Massie (D-Laramie) opposing the project (Mike Massie, pers. comm., 1999).

Based on utility requests, from 1995 to 1999 Congress considered legislation that would have established an interim storage facility for spent fuel near 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. The facility required by this legislation would contain 30,000–40,000 MTU of storage space for spent fuel. The Clinton administration continued to promise to veto any bill that would establish an interim storage site at Yucca Mountain, because it could force a decision for the permanent repository (Yucca Mountain), even if the site was not suitable.

By mid-1999 the Department of Energy and some senators offered an alternative solution to the problem. They proposed that the DOE take title to spent fuel at reactors and cover the costs of on-site dry storage. Senate leaders accepted this change but could not agree on a reformulated version of the bill. The final version of the nuclear waste bill in the 106th Congress addressed only the permanent repository as a result, and even this bill did not pass the Senate with a veto-proof margin. The bill was subsequently vetoed by President Clinton.

3. Storage cost comparison

With the amendment of the latest congressional legislation to advocate at-reactor interim storage, the argument over costs, especially who should bear the brunt of the missed 1998 deadline to move the spent fuel, continues. Utility companies that own nuclear reactors have threatened to sue the DOE for breach of contract for up to \$56 billion in damages (Kraft, 1999).[3] A summary judgement for three New England reactors (against the DOE) may result in awards of up to \$268 million

[2] 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 (Gannett News Service, 1998).

[3] The \$56 billion figure is inflated by the addition of credit card interest rates to estimates of total utility costs and refund of all past fees.

(Grunwald, 1998). Because of the potentially large amounts of money at stake, it is in the interest of all involved, including the taxpayers, to have an accurate accounting of the costs of interim storage of spent fuel.

For the United States, the question that needs to be addressed is which is the best option in terms of cost: leaving the spent fuel at reactors or moving it to an interim facility? Although economics plays a major role in the larger debate, few comprehensive and comparative economic analyses exist, virtually none outside the nuclear industry. For the purposes of example and because most cost data exists for a centralized facility at Yucca Mountain, the economic comparison given here is that of spent fuel storage at reactor sites versus centralized storage at a Yucca Mountain facility.

3.1. Results and analysis

An economic analysis of interim storage should include comparisons of capital and operating and maintenance costs between at-reactor dry storage and a centralized facility at Yucca Mountain. The analysis must also account 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; note that for at-reactor costs, the range of projected costs are derived from nuclear industry accounts and some DOE statements. The actual cost figures are taken from DOE studies, which used the nuclear industry's analysis as a basis. What follows is an explanation of the costs included in the analysis and the algorithms used to calculate total costs over time.

Capital costs for dry storage at reactors involve (1) upfront costs, which include costs for design, engineering, NRC licensing, equipment, construction of initial storage pads, security systems, and startup testing (Supko, 1998), and (2) storage system and loading costs, which include costs for storage casks, additional pads, labor, decommissioning, and consumables (TRW Environmental Safety Systems Inc., 1998). 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 these costs can no longer be charged against an operating reactor and must be fully covered on their own. 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 reactors shutdown less than 5 years, operating costs are given in Table 2. For reactors shutdown 5 years or more, pool and dry storage operating costs are $9 million per year (Office of Civilian Radioactive Waste Management, 1998). For shutdown reactors that have moved all of their spent fuel into dry storage, operating costs are $4 million per year (Office of Civilian Radioactive Waste Management, 1998).

A recent DOE report on 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 needed and costs for centralized dry storage (TRW Environmental Safety Systems Inc., 1998). The capital costs below are based on a *bare minimum* estimate of facilities required for a centralized storage facility and nothing further, and they do not include costs for facilities to handle uncanistered spent fuel, additional pools, canister lines, disposal container loading areas, and administration and medical buildings. In this analysis, capital costs to construct an independent dry storage facility near Yucca Mountain include (1) a Carrier Preparation Building, where loaded transportation casks are received, impact limiters removed, and contamination checks completed; the casks are then prepared for (2) the Waste Handling Building, where the fuel is unloaded from transport containers (TRW Environmental Safety Systems Inc., 1998, (3) a Canister Transfer Storage Module, where excess casks can be kept before processing for interim storage (this will be needed for the scenario where 3000 MT spent fuel are transported per year),[4] and (4) pads and concrete storage canisters for the spent fuel. Decommissioning costs are included as a separate capital cost because DOE does not include them in their analysis.[5] Estimates for decommissioning costs are based on 15–20% of the facility capital costs (Supko, 1998). Operating costs are also a bare minimum estimate and apply to costs accrued only from operating the Carrier Preparation Building, $44.1 million per year (without facilities for uncanistered fuel), the one Waste Handling Building, $78.8 million per year (TRW Environmental Safety Systems Inc., 1998), and those for the maintenance of dry storage facilities estimated at $4 million per year based on operating costs for an independent spent fuel storage facility (Office of Civilian Radioactive Waste Management, 1998). All at-reactor scenarios assume that no license extensions are granted to currently operating power plants.

[4] 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 (Office of Civilian Radioactive Waste Management, 1998).

[5] Decommissioning costs will depend somewhat on the availability of multipurpose casks. If storage casks are different from those emplaced in the permanent repository, then costs will increase due to the need to decommission the storage casks as well as spent fuel transfer facilities and other radioactive areas.

Table 1
Cost categories and sources for dry storage cost calculations, 1998$

Cost category	Capital costs		Operations and maintenance	
	Upfront costs	Storage system and loading[a]	Operating reactor costs	Shutdown reactor costs
At-reactor dry storage	$9 M/site[b]	$60,000[c]–$80,000[b]/MTU	$470,000[d]–$750,000[b]/yr/site	$4–9 M/yr/site[e]
Centralized interim facility	$680 M[f]	$60,000[c]–$80,000[b]/MTU	$127 M/yr[g]	
	Nevada transport	Civilian transport and operations		
		Mobilization and acquisition	Waste acceptance and 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]Nigel Mote (pers. comm., 1999) 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). See Table 2 below for reactors shutdown less than 5 years.
[f]TRW, 1998, Table E-1. Costs are for construction of a Canister Transfer Module, one Waste Handling Building, and one additional Canister Transfer Storage 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/yr).
[h]TRW, 1998. Nevada transport is for either heavy-haul trucks or new railroads from Caliente, NV to Yucca Mountain.
[i]TRW, 1999.This number includes costs to develop transportation schedules, license and procure transportation equipment, and develop contracts with rail and truck lines for shipping. This figure represents 78.4% of the total transportation costs for this category, which are those to be borne by the civilian sector.
[j]TRW, 1999.This cost covers the costs of shipping *all* spent fuel at reactors to Yucca Mountain. This figure represents 78.4% of the total transportation costs for this category, which are those to be borne by the civilian sector.

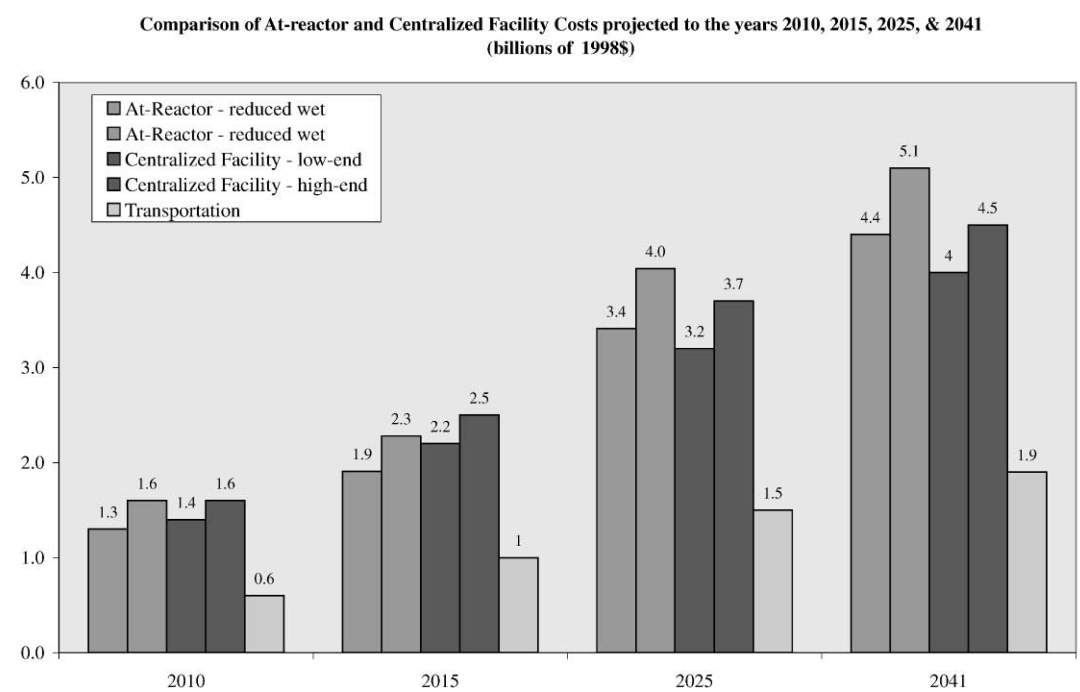

Fig. 2. Cost comparison for capital, operating and maintenance, and transportation costs for interim storage of spent fuel for the 2010, 2015, 2025, and 2041 cases. Medium gray boxes refer to the at-reactor storage, high and low estimates, darker gray boxes represent centralized facility storage, and light gray boxes represent transportation costs accrued for centralized facility storage. All costs are in 1998$. See text for details.

All transportation costs presented here are based on estimates provided by DOE analyses (see Table 1 and Fig. 2). A large portion of the 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, NV to the proposed storage facility adjacent to Yucca Mountain. Caliente, Nevada 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, Nevada, to Yucca Mountain. Various routing options exist and account for the variation in cost (Table 1). Another option is to forego the more expensive but potentially safer rail line and use heavy-haul truck transport from Caliente through the center of downtown Las Vegas to Yucca Mountain. 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 points 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 (TRW Environmental Safety Systems Inc., 1998). Costs for the transportation operation of all civilian spent fuel (Table 1) are estimated to be 78.4% of total transportation costs (which include high-level waste from DOE facilities) (TRW Environmental Safety Systems Inc., 1999). The transportation and operations cost estimate in Table 1 does not include costs for development and evaluation of waste acceptance, storage, and transportation (estimated to be $36 million between 2000 and 2005; TRW Environmental Safety Systems Inc., 1999).

Fig. 2 provides a comparison of costs of on-site, at-reactor dry storage versus centralized dry storage costs versus transportation costs, projected out to the future for four cases: 2010, 2015, 2025, and 2041 (where 2041 represents the last year of spent fuel transport according to DOE estimates (TRW Safety Systems Inc., 1999)).[6] At-reactor costs to utilities 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 are calculated for a centralized facility that is completed and begins to accept spent fuel by 2005, according to DOEs transportation schedule. For example, in the 2010 case, the costs would be based on the amount of spent fuel received at the centralized facility between 2005 and 2010. Transportation costs in Fig. 2 are calculated by discounting the per-year costs[7] to 1998 from 2010, 2015, 2025 or 2041, depending on the case, and adding them together over the specified time period (Office of Civilian Radioactive Waste Management, 1998).

The following equation describes the at-reactor costs accrued between 1998 and 2010:

Cost per reactor site $= \Sigma_{i=x-1998}^{i=y-1998}(\mathrm{SC}\times A_i)/(1.05)^i + U/(1.05)^{x-1998} + \Sigma_{i=x-1998}^{i=y-1998}(\mathrm{OC}/(1.05)^{i+1})$ where SC is the unit storage system and loading costs, which includes the decommissioning costs (see Table 1), A is the amount of dry storage required for a particular year i, $\mathrm{SC}\times A$ is discounted to y, the year before dry storage is required from the year 2010, 2015, 2025, or 2041, depending on the case, U are the upfront costs, $9 million, calculated the year of start of dry storage, x, OC are the annual operating costs, calculated beginning the year of start of dry storage, $x+1$, and discounted from 2010, 2015, 2025, or 2041. The discounting of 1998 dollars is done at a nominal rate of 5% over the entire time period, based on average and projected discount rates provided by the Office of Management and Budget (1999).[8] The storage system and loading costs, SC, are calculated using both $60,000/MTU spent fuel and $80,000/MTU, and the operating costs are calculated using both $470,000/yr/site and $750,000/yr/site (see Table 1), to give a high and low value for each case (Figs. 2 and 3). Estimates of the amount of dry storage required, A, are based on averaged actual annual discharges of spent fuel. In this study, a reactor is assumed to require additional spent fuel storage according to utility estimates of loss of full-core off-load (Nuclear Regulatory Commission, 1998). Once the pool is full (minus one full-core amount of fuel) the amount discharged per year is assumed to be transferred to dry storage. The SC and U costs are paid the year before dry storage is needed in the above calculations. For those reactors that already have dry storage on site, no additional U costs are paid. The OC costs are paid beginning the year of full-core off-load loss, or the year of dry storage use. Once a reactor shuts down, OC costs follow Table 2, depending on the number of pools and the number of reactors at the site. After a reactor has been shutdown for 4 years, in the 5th year all spent fuel is assumed shifted to dry cask storage to take advantage of lower OC costs. The amount of this spent fuel is based on the amount of pool capacity from utility data (Energy Information Administration, 1996) minus a full core's worth of spent fuel (or two full cores if two reactors share one pool).

[6] 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, another 37 reactors will close. By 2041, all reactors are shutdown in this model, assuming no license extensions.

[7] The Total System Life Cycle Costs (Office of Civilian Radioactive Waste Management, 1998) provide a year-by-year breakdown of transportation costs, including Nevada transport costs.

[8] The discount rate could be adjusted to fit more recent OMB estimates, but since all costs in this study are discounted by the same rate, all costs would change proportionately. The important point in this analysis is that the relative, not absolute, figures are the most meaningful.

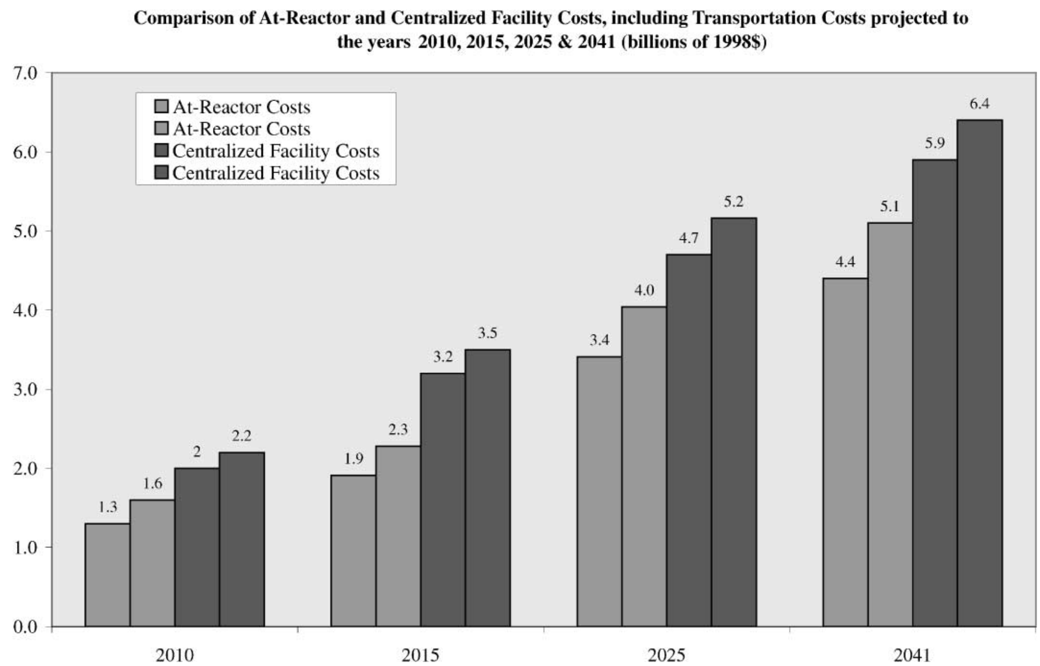

Fig. 3. Cost comparison of at-reactor and centralized storage of spent fuel for the 2010, 2015, 2025, and 2041 cases. Transportation costs are included in the centralized cost estimates in this figure. Medium gray boxes refer to the at-reactor storage, high and low estimates and dark gray boxes represent centralized facility storage. All costs are in 1998$.

Table 2
Annual costs for pool operations and maintenance at shutdown reactors, 1998$ (for reactors shut down less than 5 years)[a]

No. of shutdown reactors at a site	No. of pools on site	Costs by number of reactors on site		
		1	2	3
1	1	$4,675,024	—	—
1	2	—	$738742	$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 shutdown 5 years or longer, if no other pools are operating, then the operating costs jump to $9 M/yr. For reactors that move all their spent fuel into dry storage (instead of continuing to operate pools), like Trojan in Oregon, operating costs once all the fuel is in dry storage are $4 M/yr.
Adapted from TRW Systems Analysis, 1993.

Total cost estimates for a centralized storage facility at Yucca Mountain is based on the following equation:

$$\text{Cost for centralized facility} = \sum_{i=2005-1998}^{i=y-1998} \mathrm{SC} \times A_i/(1.05)^i + U/(1.05)^3 + \mathrm{DC}/(1.05)^{52} + \sum_{i=2005-1998}^{i=y-1998} (\mathrm{OC}/(1.05)^i),$$

where SC is the cost for the unit storage system and loading, A is the amount of dry storage required by 2010 (10,200 MTU), 2015 (25,200 MTU), 2025 (55,200 MTU), and 2041 (86,317 MTU) based on DOE's schedule for moving spent fuel from utilities (TRW Safety Systems Inc., 1999), for transportation beginning in 2005, $\mathrm{SC} \times A$ is discounted to the year before storage is required, 2004, from 2010, 2015, 2025, or 2041, depending on the case, U is the capital cost of $680 million for the Carrier

Preparation Building, the Waste Handling Building, and the Canister Transfer Storage Module, discounted from 2001, assuming a centralized facility will be ready to accept waste in 2005, DC are the decommissioning costs, ranging from 15 to 20% of the capital costs ($SC \times A + U$) discounted from 2050, OC are the annual operating costs, $127 million, discounted from 2010, 2015, 2025, or 2041, y is the year the case ends (2010, 2015, 2025 or 2041), and i represents the number of years from 2005.

Costs for transportation are calculated using year by year cost estimates provided in Table C-1 of the DOEs *Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program* (Office of Civilian Radioactive Waste Management, 1998). These costs, which include Nevada transportation costs and the waste acceptance and transportation operations costs, are discounted at the 5% rate. Added to these costs are the mobilization and acquisition costs of $86 million, discounted from a 2005 pay date.

Fig. 2 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 (Fig. 3). These costs, of course, may be recouped if a permanent repository opens at Yucca Mountain, 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 after opening, then the loss to the taxpayer is on the order of billions of dollars.

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 (Fig. 2). 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 (Fig. 4). For the at-reactor case, if spent fuel is not moved from wet to dry storage at shutdown reactors, then operating costs dominate (from the operation of reactor pools) and their percentage of the total costs increases with time. When spent fuel is moved to dry storage 5 years after reactor shutdown, with time OC or operating costs approach those of SC costs (Fig. 4). For the centralized facility case, in 2010 the costs are fairly evenly divided among the storage system, upfront, and operating costs, but storage system capital costs dominate by 2015 (Fig. 4). Fig. 4 provides a few comparisons between the at-reactor and centralized cases. First, upfront costs are consistently higher for centralized storage than for at-reactor storage (Fig. 4). In fact, the analysis here most likely underestimates the upfront costs for centralized storage by accounting only for two initial waste buildings. Actual upfront costs may be a few hundred million dollars higher if additional buildings are added. Second, although SC costs are similar between the at-reactor and centralized cases over the entire time examined, OC costs for the at-reactor case outpace Centralized OC costs, especially by the 2041 case.

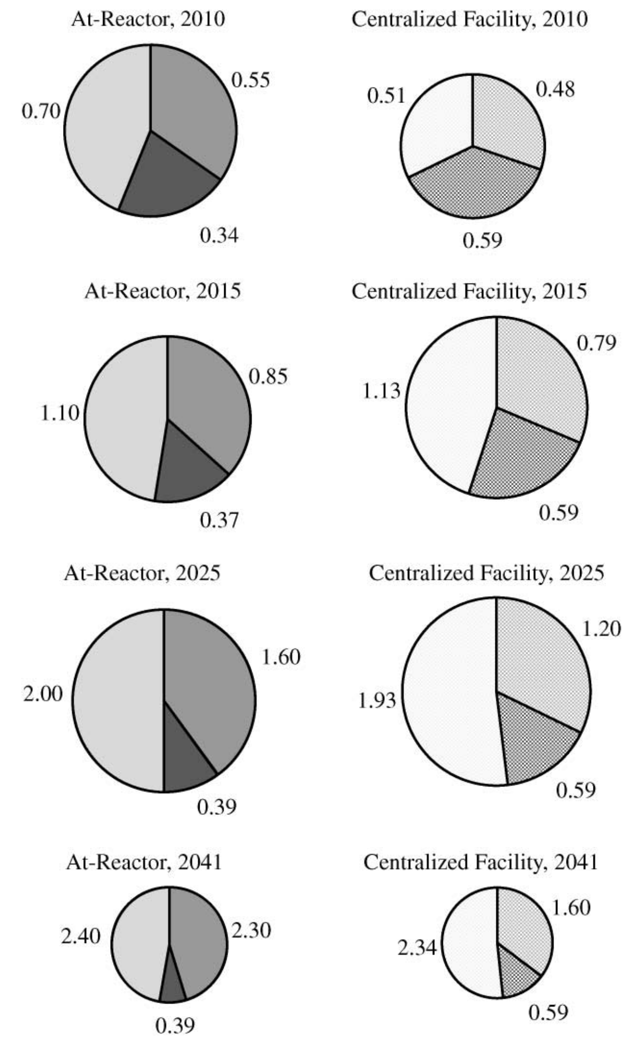

Fig. 4. Cost breakdown for at-reactor and centralized facility spent fuel storage for the 2010, 2015, 2025, and 2041 cases. At-reactor costs are in the left-hand column; centralized facility costs are in the right-hand column. OC are operating costs, medium gray color; U are upfront costs, dark gray color; and SC∗A are storage and loading costs, light gray color. Note that in both the reactor and centralized plots, decommissioning costs are included as part of the SC∗A costs. Details in text.

Centralized storage of spent fuel, then, becomes an economically better option only if spent fuel is to be stored for at least five decades before a permanent repository is available. The trend in Fig. 2 suggests that after 50 years or more, centralized storage will become the more economic option. This conclusion presupposes that no permanent repository becomes available during these 50 years, which is unlikely. As Fig. 3 shows, high transportation costs offset any savings after 50 years. For a centralized facility to be economically viable, transportation costs must be reduced. This cost reduction could be done in part by reducing transport distances and locating a centralized facility closer to reactors. A more thorough economic analysis of alternate centralized facility options is required to establish whether enough savings could be gained to make such an option less expensive than at-reactor storage. Based on the analysis in this paper, and given that a permanent repository may open at Yucca Mountain in the next 20 years, it is clear that there is no economic advantage to using a large-scale centralized spent fuel storage facility.

3.2. Comparison to industry analysis

The nuclear industry (represented by the Nuclear Energy Institute, NEI) calculated costs for interim storage of spent fuel as compared with centralized storage, and based on their calculations, determined that at least $5 billion would be saved with a centralized facility (Table 3; Kraft, 1999). This conclusion is in marked contrast to my conclusions that show no savings gained by a centralized facility. In part, this discrepancy is due to different methods and assumptions used in our calculations. In my calculations, I chose a year in the future (2010, 2015, 2025, and 2041) and then calculated the costs accrued at individual reactors and at a centralized storage facility up to that year. For the centralized facility case, I assumed it would open in 2005. All my costs were discounted. In its calculations, NEI assumed for the at-reactor case that DOE acceptance of spent fuel for disposal in a permanent repository began in a certain year (2010 or 2015) and then calculated the *total* future costs to utilities (projected to 2041 for the 2010 case and 2046 for the 2015 case) (Eileen Supko, pers. comm., 1999). They then compared these numbers to the (imaginary) case where DOE acceptance for centralized storage began in 1998. None of their cost figures were discounted. Discounting future values to the present takes into account the fact that a dollar today is worth less in the future, and as a result, it provides a more realistic perspective on these costs, almost all of which will be paid in the future.

There are further significant differences between our calculations. First, the savings that NEI calculated were a centralized facility to be used (Table 3) are actually savings to the federal government and nuclear industry as a whole. According to NEIs calculations, the utilities would see a greater savings ($7.3 billion for their 2010 case and $10.5 billion for their 2015 case) than those they claim ($5 billion for the 2010 case, $8.2 billion for the 2015 case), whereas the federal government would experience a loss of $2.3 billion in either case.

Furthermore, according to my analysis of DOE cost estimates for centralized storage at Yucca Mountain, NEI underestimated these costs. They suggest that the price tag for centralized storage, including operations and capital costs, from 1998 to 2041 would be $2.3 billion. My estimate of the cost of a centralized facility from 2005 to 2041 is between $4 and $4.5 billion, over $1.7 billion more.

Perhaps more significant is the way in which NEI treated dry cask costs in their calculations. For the centralized storage case (the 1998 case in Table 3), NEI assumed that storage casks would be disposal casks as well. In other words, the casks used for dry storage at a centralized facility would be the ones to go directly into a geologic repository. This is an unrealistic assumption given that the DOE has yet to decide on the ultimate design for the repository casks. The prospect of a disposal cask being licensed in the next 5 years is quite low. Furthermore, for the at-reactor cases (2010 and 2015 in Table 3), NEI has listed item lines for dry-storage casks

Table 3
Industry estimates of interim storage costs (billions of 1997$)[a]

Acceptance	1998	2010	2015
Dry storage required	3300 MTU	16,200 MTU	22,000 MTU
Utility costs			
Dry storage	0.5	1.4	1.6
Storage after shutdown	5.8	12.2	15.2
Total utility costs	6.3	13.6	16.8
Federal system costs			
Interim storage facility	2.3	0	0
Canisters	5.9	5.9	5.9
Acceptance and transportation	3.8	3.8	3.8
Repository	25.5	25.5	25.5
Total federal costs	37.5	35.2	35.2
Total life cycle costs	43.8	48.8	52
Interim storage savings		5.0	8.2

[a] Reproduced from S. Kraft, Temporary Interim Storage of Spent Nuclear Fuel, Presentation at the Workshop on Interim Storage of Spent Fuel and Management of Excess Fissile Material, Harvard University, February 18, 1999.

at reactor sites *and* for repository disposal casks, driving up the costs for the at-reactor case compared to the centralized case. This inconsistency is simply not good accounting. It is certainly not accurate to double-count casks in one case and single-count them in another — the totals are not comparable. It would be more rigorous to list cask costs (as I have done in my analysis) only once and leave the issue of repository casks to another analysis.

The nuclear industry claims a potential $56 billion federal liability if a spent fuel is not soon collected from the sites. The $56 billion is based on high-end estimates of utility costs in 1997 dollars ($1.2 billion for on-site storage and $18.4 billion for storage post shutdown), fees paid into the NWPA ($8.5 billion), and lost opportunity on the NWPA fees (at 14%, $27.8 billion) (all 1997 dollars, Kraft, 1999). This claim is rather different from the $7.3–10.5 billion the industry calculated would be paid by utilities as a result of DOE's breach of contract, even if interest is added to these figures.

4. Implications for other facilities

As discussed in the beginning of this paper, two privately funded large-scale centralized storage facilities are currently being developed in the United States. It is not clear yet whether they will be granted operating licenses, and moreover, if licensed, it is not certain how smoothly they would operate, given the political opposition to them. The Goshute facility in Utah faces stiff opposition from state officials, who would likely seek to delay the opening of an interim storage facility through lawsuits and by imposing new state regulations. Planning for the Owl Creek facility in Wyoming is not as advanced as that of the Goshute site. Therefore, it is difficult to know the intensity of public opposition in Wyoming, although small groups that oppose the facility have been in existence for a number of years.

Based on the analysis here, neither facility would have an economic advantage over at-reactor storage. Both the Goshute and the Owl Creek facilities suffer from the same scale of transportation problem that would afflict a centralized storage facility at Yucca Mountain, because they are all located so far from operating reactors (Fig. 1). As the economic analysis in this paper shows, it will be cheaper for a reactor to provide dry storage on site than to send its spent fuel to a storage facility if the reactor has to cover the costs of transportation of its spent fuel. Moreover, the fact is that most utilities will have to buy some amount of dry storage for their spent fuel, and even if a permanent repository is available by 2010 and spent fuel transport begins before then, DOE or private facilities simply cannot transport all excess spent fuel at once (see Macfarlane, 2001). So, in effect, utilities may pay twice for their spent fuel storage. As a result, only those utilities (1) whose future operations are threatened if they cannot find out-of-state storage space and (2) who see a political gain (by obtaining public approval for license extension, for instance) in sending their spent fuel off site, will be interested in paying a higher price for interim storage.

5. Moving towards a solution

Although no US reactor has yet shutdown because of a lack of spent fuel storage space, in it not clear whether this trend will continue. 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. For example, Northern State 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 (Nuclear Energy Institute, 1999). 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 (Nuclear Energy Institute, 1999).

There is, perhaps, a better way to come to the aid of over-capacity reactors: create a small (2000–5000 MTU) off-site storage facility, similar to that envisioned by the MRS Commission (Monitored Retrievable Storage Commission, 1989). This facility would not be as costly as a large plant, like that envisioned for Yucca Mountain, and transportation costs would be reduced by locating it on the East Coast or in the Midwest, nearer the bulk of the reactors. Most of the dry storage costs would be incurred by on-site dry storage at reactors, except for those reactors that would be faced with shutdown if they were to expand on-site dry storage. The utilities that own these reactors would presumably be willing to share the costs for such a facility.

To overcome political obstacles, the small storage facility should be located in a place that already has experience with nuclear power and nuclear materials and where the local community is predisposed to accept such a facility. To ensure equity for both the public and the nuclear industry, it should not be located in Nevada or in a state that has imposed restrictions on the amount of spent fuel allowed in dry storage. Keeping it small, on the order of a few thousand MT of spent fuel, would ensure that it will not become a de facto or "permanent" repository for the entire nation's spent fuel, any more than a reactor will. Eventually, the spent fuel located there will be moved to a permanent geologic repository.

In the 1980s there was, in fact, a proposal to site an interim storage facility in the United States in a locale that was accepting of such a facility: Oak Ridge, Tennessee, home of the Oak Ridge National Laboratory, which produced uranium for nuclear weapons and now stores most of DOE's supply. Due to its central location among 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 (New York Times, 1985). 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 (Isaacs, 1993). 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.

For a small facility, it would be best to consider either a utility that has already-existing storage space or a federal facility with the ability and space to handle dry storage. Space at a utility-owned site would be in the form of cooling pool space or the ability to handle a few thousand MTU of dry storage such as Fort St. Vrain in Colorado or the Morris site in Illinois. Utilities may see a financial gain in providing this service that would offset political liabilities. Perhaps the Owl Creek facility could be scaled down to a smaller facility, but the storage fees may not offset the capital and transportation costs. A safer bet would be a federally owned site, or two federally owned sites such as Oak Ridge, the West Valley site in New York state, or the Savannah River site in South Carolina.

It is possible to resolve the problem of how to manage spent fuel until a permanent solution is available. On the other hand, a proposal to solve the problem that is not economically viable, in comparison to cost-saving alternatives, will not win public support. Moreover, as experience has shown, public support is necessary to the survival of the nuclear energy industry — especially if they are looking to be the answer to global climate change.

References

Associated Press, 1998. Hearings to start on tribe's nuclear dump plan. Las Vegas Review Journal, Las Vegas, January 27, p. 8B.

Black, R.W., 1999. Nuclear Storage Facility Could Create 3000 Jobs, Study Shows. Associated Press, Cheyenne.

Carter, L., 1994. The Mescalero option. Bulletin of the Atomic Scientists, September/October, pp. 11–13.

Dow Jones and Company, 1996. Northern States says talks with Apaches on spent fuel falter. Wall Street Journal, New York.

Energy Information Administration, 1996. Spent Nuclear Fuel Discharges from U.S. Reactors 1994, SR/NEAF/96-01. Department of Energy, February.

Gannett News Service, 1998. Tribes asserting sovereignty in waste, casino controversies. The Salt Lake Tribune, Salt Lake City, December 28.

Gerrard, M.B., 1994. Whose Backyard, Whose Risk: Fear and Fairness in Toxic and Nuclear Waste Siting. MIT Press, Cambridge, MA, 335pp.

Grunwald, M., 1998. Nuclear Waste Disposal Still a Festering Problem, Firm Wins Damages over U.S. Inaction. Washington Post, WA, November 22.

Hanson, R.D., 1998. From environmental bads to economic goods: marketing nuclear waste to American Indians. Ph.D. Thesis, University of Minnesota.

Holt, M., 1998. Civilian Nuclear Waste Disposal. 92059. National Institute for the Environment, April 24.

Isaacs, T., 1993. What will happen to our nuclear waste? In: Golay, M. (Ed.), Second MIT International Conference on the Next Generation of Nuclear Power Technology. MIT, Cambridge, MA, pp. 6-2-6-10.

Kraft, S., 1999. Temporary interim storage of spent nuclear fuel. Workshop on Interim Storage of Spent Fuel and Management of Excess Fissile Material, Harvard University, February.

Macfarlane, A., 2001. Heated decision: prospects for the interim storage of spent fuel in the United States. Belfer Center for Science and International Affairs Working Paper, Cambridge, MA.

Monitored Retrievable Storage Commission, 1989. Nuclear Waste: Is There a Need for Federal Interim Storage? Monitored Retrievable Storage Commission, November 1.

New York Times, 1985. Tennessee battles with U.S. in nuclear waste program. New York Times, New York, September 3.

Nuclear Energy Institute, 1999. Used Nuclear Fuel.www.nei.org/finance/digest.html, October.

Nuclear Regulatory Commission, 1998. Reactor Spent Fuel Storage. www.nrc.gov/OPA/drycask/sfdata.htm.

Office of Civilian Radioactive Waste Management, 1998. Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program. DOE/RW-0510, Department of Energy, December.

Office of Management and Budget, 1999. Circular No. A-94, Appendix C: Discount Rates for Cost-Effectiveness, Lease Purchase, and Related Analyses, January.

Supko, E.M., 1998. Minimizing risks associated with post-shutdown spent fuel storage and LLW disposal. In: Nuclear Power in the Competitive Era.

TRW Environmental Safety Systems Inc., 1998. CRWMS Modular Design/Construction and Operation Options Report. A00000000-01705700-00022 Rev. 02, Department of Energy, December 18.

TRW Environmental Safety Systems Inc., 1999. Report to Update Total System Life Cycle Cost Estimates for Site Recommendation/License Application. TDR-CRW-SE-000001 REV 1, Department of Energy, December.

TRW Systems Analysis, 1993. At Reactor Dry Storage Issues, E00000000-01717-2200-00002 Rev. 1, Department of Energy, December 10.

Woolf, J., 1997. Is the West to Become Nuclear Waste Land? Salt Lake Tribune, Salt Lake City, October 5, p. A10.