INTRODUCTION

Spent nuclear fuel storage is a required step in all open and closed fuel cycles. This is a consequence of the nuclear characteristics of SNF. The radioactivity decreases rapidly with time resulting in radioactive decay heat and gamma radiation decreasing rapidly with time. There are large safety and economic incentives to allow the radioactivity of SNF to decrease before transport, processing, or disposal.

Upon reactor shutdown, SNF is intensely radioactive and generates large quantities of decay heat—equal to about 6% of the power output of the reactor. However, the radioactive decay heat decreases very rapidly reaching 0.5% in one week. The refueling strategy in LWRs is to transfer the SNF from the reactor core to the SNF storage pool (Fig. 1) where the water provides cooling and radiation shielding. In the following decade, the radioactivity after the first rapid decrease in radioactivity will decrease by another factor of 100. Reactor SNF storage is a safety function to provide time for the SNF decay heat to decrease sufficiently that a serious accident can no longer happen.

Figure 4.1  Wet Storage System — Spent Fuel Pool
If SNF is to be shipped, typically the minimum time before SNF shipment is 2 to 3 years. However, there are large economic incentives to store SNF for a decade before transport. SNF is shipped in heavy steel casks. With short-cooled SNF, thicker walls are required to provide radiation shielding resulting in less SNF per cask. Cask capacity is also limited by the requirement to limit SNF temperatures to avoid SNF degradation. The radioactive decay heat must be conducted out through the cask walls. A decade of storage enables the use of more-economic large-capacity casks that minimize the number of shipments.

SNF can be transferred for storage from the SNF pool to dry cask storage (Fig. 2). Dry cask storage is a preferred option for long-term storage of SNF because the cask has no moving parts (natural circulation air-cooling for decay heat removal) and requires very little maintenance. Like transport casks, there are economic incentives to store the fuel in the pool for a decade before transfer to dry cask storage.

**Figure 4.2 Schematics of Dry Cask Storage Systems**

![Figure 4.2 Schematics of Dry Cask Storage Systems](image)

**Figure 4.3 Independent Spent Fuel Installation - Dry Cask Storage**

![Figure 4.3 Independent Spent Fuel Installation - Dry Cask Storage](image)
If SNF is to be disposed of in a repository, it will be stored for 40 to 60 years (Chapter 5: Waste management). Peak temperatures in a geological repository are limited to assure long-term repository performance. If the temperatures are too high, the performance of the waste form, waste package, and geology may be impaired. Peak repository temperatures are controlled by limiting the allowable decay heat per waste package. If the SNF is stored for several decades, the decay heat per ton of SNF decreases, more SNF can be placed in each waste package, the waste packages can be spaced closer to each other underground, the size (footprint) of the repository is reduced, and the cost of the repository is reduced. Like the SNF, the HLW will be cooled for 40 to 60 years before ultimate disposal to reduce the decay heat.

SNF sent to a reprocessing plant may be stored for long periods of time before reprocessing.

- **Product specifications (Appendix E: Status of Fuel Cycle Technology).** In closed fuel cycles, SNF is converted into fresh fuel assemblies and wastes for disposal. One complication is that each SNF assembly has different plutonium isotopics. To fabricate fresh fuel assemblies with the proper plutonium isotopic content, selected SNF assemblies are chosen so when reprocessed together as a batch, the plutonium isotopic specifications for the plutonium fuel are met (Appendix E). This is conceptually similar to the recycle of steel where different grades of scrap metal are mixed together to produce a recycle steel that meets product specifications. In both cases, large inventories of recycle materials help provide the right selection of feed materials to produce the desired products.

- **Reduced reprocessing costs.** As SNF ages and its radioactivity and decay heat decrease, it becomes easier and less expensive to reprocess.

The requirement for SNF storage to allow decreases in decay heat resulted in several countries building centralized facilities for SNF or HLW storage in the 1980s to age the wastes before disposal. The U.S. passed laws requiring disposal of SNF on a specific schedule without considering storage; however, those legal requirements did not change the need for storage. The technical solution at the proposed Yucca Mountain repository was to place the SNF in waste packages, put the waste packages in the repository, and cool the repository with air flow through the disposal drifts for 50 years after the repository was filled. The strategy of SNF storage (at the reactor, a centralized storage facility, or a ventilated repository), wherever it is done, significantly reduces the size and cost of the repository. In effect, the proposed Yucca Mountain repository would have been functionally a SNF storage facility that would be functionally converted into a geological repository after the 50-year cooling of the SNF.

**RECOMMENDATION FOR SNF STORAGE FOR UP TO A CENTURY**

Technical and economic factors define nominal SNF storage times—60 to 70 years in the proposed Yucca Mountain system. These storage times may be increased or decreased by policy considerations. Technical and policy considerations have led to our recommendation that:

*Planning for long term managed storage of spent nuclear fuel—for about a century—should be an integral part of nuclear fuel cycle design.*

SNF is a significant potential source of energy; however, we do not know today if LWR SNF is a waste or a valuable national resource. Because of this uncertainty, we recommend
There is no incentive today to recycle SNF. Economic uranium resources will be available for most of this century (Chapter 3). Current waste management technologies can safely dispose of SNF (Chapter 5). The cost to recycle LWR SNF is greater than making new fuel from mined uranium (Chapter 7).

The energy content of SNF is significant and thus the incentive to maintain the option of future use of SNF. The historical vision of the future of the nuclear fuel cycle was that LWR SNF is a valuable resource. Plutonium from LWR SNF was to be recovered and fabricated into fuel for the startup of fast reactors. Such a system could increase the available energy from uranium by more than an order of magnitude.

New fast-reactor technologies may not require plutonium from LWR SNF. Advances in technology indicate that fast reactors may be started up on low-enriched (<20% $^{235}$U) uranium and thereafter continue operation with fast reactor SNF recycle and the addition of depleted or natural uranium. If successfully developed, this technology would have today significantly lower costs than startup of fast reactors with plutonium recovered from LWR SNF. With startup on low-enriched uranium, fast reactor deployment would not be limited by the availability of plutonium from the reprocessing of LWR SNF—a strategy that also reduces long-term uranium demands by allowing the option of large-scale deployment of fast reactors earlier in time (Chapter 6). Fast reactor SNF has a fissile content an order of magnitude higher than LWR SNF—thus the economics of recycling fast reactor SNF may be different than for LWR SNF.

Long transition times to new fuel cycles. Dynamic modeling of alternative fuel cycles (Chapter 6) reveals that the transition from one fuel cycle to another takes 50 to 100 years. This reflects the long lifetimes of nuclear power plants and the several decades for the industrial implementation of any alternative fuel cycle. It implies that if we knew what future fuel cycle we wanted, the planning horizon for SNF storage would be on the order of 50 to 100 years. Today we do not have the information to make wise decisions on what fuel cycle or fuel cycles we should adopt: the future scale of nuclear power is uncertain—a factor with major implications on fuel cycle choices, alternative fuel cycle options have been identified but it will take time to understand what the preferred option or options are, and the preferred economic choices are unclear. There is also no national consensus on what should be our fuel cycle goals (Chapter 2) but some type of broad consensus is required for any option requiring several decades to fully deploy.

This recommendation is not a recommendation to slow the development of a geological repository. Permanent geological isolation will be required (Chapter 5) for at least some long-lived components of SNF, and so systematic development of a geological repository needs to be undertaken. Furthermore, the U.S. has today significant inventories of defense high-level waste and small quantities of commercial high-level glass that are ready for geological disposal. Rather our recommendation is based on the benefits to maintain future options, the benefits to waste management of SNF storage before disposal, and the relatively low-cost of SNF storage.

Storage is a viable option because the quantities of SNF are small and the costs of storage are small relative to the value of electricity produced. A typical reactor produces 20 tons of SNF per year. The U.S. generates ~2000 tons of SNF per year in the process of producing ~20% of a policy that maintains fuel cycle options—long-term storage of SNF. There are several factors that lead to this conclusion.
Intergenerational Equity

Intergenerational equity addresses the issue of burdens and benefits to different generations. The “achievement of intergenerational equity” is one of the cornerstones of nuclear waste management and one of the reasons for choosing geological repositories for the ultimate disposal of nuclear waste so as to minimize burdens to future generations. In the context of SNF storage, there are benefits to maintaining options for future generations and burdens associated with storage.

We undertook a study on intergenerational equity to understand and clarify these issues in the broad context of sustainability and fuel cycle choices. The study puts forward a way of assessing future fuel cycles in accordance with the intergenerational equity criteria presented as a broadly defined set of moral values built around the principle of sustainability. These values are characterized as moral values since they contribute to the environment and humankind’s safety and security as well as an overall welfare of society in terms of sustainability. A summary of our analysis is in Appendix D.

In the context of spent fuel, an important conclusion of the analysis is that net risks and benefits are partly dependent upon the availability of future technologies. Preservation of options also argues for repository design with reversibility and retrievability. This points to an important benefit of preserving options that do not elevate risk. This has been the subject of recent major international studies.¹

OPTIONS FOR LONG-TERM SNF STORAGE

There are many options for long-term storage of SNF. The three major options for LWR SNF are: pool storage at the reactor or a centralized site, dry cask storage at the reactor or a centralized site, and storage in a repository to allow retrievability. All can provide long-term safe SNF storage. Centralized storage has become the preferred option for most countries (France, Japan, Sweden, etc.) with significant nuclear power programs.

All LWRs use short-term pool storage of SNF. Pool storage is used for centralized long-term storage of SNF at the CLAB facility² in Oskarshamn, Sweden. This facility, located 30 meters underground, has a capacity of 8000 tons of SNF with a current inventory of 5000 tons. It opened in 1985 with the specific goal to store SNF until the decay heat decreased sufficiently for disposal in the planned Swedish repository at Forsmark. When CLAB was built, pool storage was the only technology for long-term storage of SNF. Pool storage is also used at reprocessing plants because it allows easy retrieval of specific fuel assemblies to be reprocessed as a batch. France, Russia, Great Britain, and Japan have centralized pool storage of SNF to support their associated reprocessing plant operations. In the U.S., General Electric built a medium-size reprocessing plant at Morris, Illinois but technical difficulties were found during testing; thus, the plant was never operated. The storage pool built to support that plant is now a centralized SNF storage facility for the SNF that was to have been reprocessed.
Dry cask storage is used for short and long-term storage of SNF. As discussed later in this chapter, it is a modular storage technology that is the chosen long-term SNF storage technology in the United States and is used around the world. Dry cask storage is also used for centralized SNF storage in Germany at Gorleben.

Repositories can be designed for retrievable SNF storage. The proposed Yucca Mountain Repository in the United States was designed to remain open for 50 years after final loading of SNF to provide air cooling of waste packages with the option for retrievability if safety issues were found with the repository. The French repository is designed to enable waste recovery for extended periods of time to provide higher confidence to the public. There are also repository designs to enable SNF recovery in salt and other geologies. In these examples the SNF is designed to be retrievable to meet a variety of different goals. There would be limited design modifications if the goal was retrievability with the policy goal of maintaining the option to recycle SNF.

**SNF Storage for the United States**

*The possibility of storage for a century, which is longer than the anticipated operating lifetimes of nuclear reactors, suggests that the United States should move toward centralized SNF storage sites—starting with SNF from decommissioned reactor sites and in support of a long-term SNF management strategy.*

Ideally such storage sites would be at repository sites or at sites capable of future expansion to include reprocessing and other back end facilities if the U.S. chooses a closed fuel cycle. While this recommendation is made in the context of a better long-term fuel cycle system, it also addresses two near-term issues: SNF at decommissioned sites and federal liability for SNF storage.

The federal liability for SNF storage is a result of changing federal policies and delays in the repository program. At the time when most nuclear power plants were built in the United States, it was assumed that LWR SNF would be reprocessed. The plants were built with limited SNF storage capacity because of the expectation that SNF would be shipped within a decade to reprocessing plants for recovery and recycle of plutonium.

The U.S. government decisions in the 1970s to not allow commercial reprocessing and the resultant national decision to directly dispose of SNF ultimately led to a decision to ship SNF from reactors directly to a geological repository. Under the Nuclear Waste Policy Act, utilities signed contracts with the federal government for disposal of SNF with removal of SNF from reactor sites starting in 1998. As reactor SNF storage pools filled and it became evident that the U.S. government would not meet its contractual obligations to receive SNF, utilities began to construct modular dry cask storage systems for their SNF to enable continued operations of the reactors.

There is a growing national taxpayer obligation to utilities for failure of the Department of Energy to remove spent fuel beginning in 1998 from nuclear plant sites according to contracts signed with the DOE. The costs are meant to cover the expenses utilities have incurred to build their own dry cask storage facilities at their sites. It is estimated that this obligation would total $11 Billion by 2020. By that time most of the utilities will have built
their own Independent Spent Fuel Storage Installations (ISFSI) for which the government will have to pay under court decisions.

We analyzed SNF storage costs for at reactor and consolidated SNF storage to understand the economic implications of alternative SNF storage strategies. These “sunk” costs affect the economics of building a central spent fuel storage facility since the marginal cost of operating an ISFSI while a nuclear plant is operating is relatively small. Thus, when the ongoing costs of paying utilities for at-reactor storage are included as a sunk cost, these expenses plus those of building a centralized ISFSI and transporting spent fuel from operating sites is likely not to be economically justified since it does not reduce costs but adds to the costs of waste management. This is not true for sites that have been decommissioned leaving only the ISFSI in place with relatively high annual operating costs which the government (taxpayer) is also obligated to pay. By clearing these sites, the government obligation ceases.

The most recent capital cost estimate for a centralized ISFSI of 40,000 MTHM (20 years of SNF generation in the United States at the current rates) is about $560 Million which includes design, licensing, and construction of the storage pad, cask handling systems, and the rail infrastructure (locomotive, rail cars, transport casks, etc). Annual operating costs during loading are estimated to be $290 million per year which includes the costs of the dual purpose canisters and storage overpacks. Fully loading this size ISFSI will take 20 years followed by a period of “unloading” and eventual decommissioning. The middle period of “caretaking” is estimated to cost about $4 million per year compared to caretaking decommissioned reactor costs for $8 million per year per site. The cost savings from consolidating the spent nuclear fuel from decommissioned sites is a compelling motivation for the federal government to create a centralized storage installation or facilitate transfers between decommissioned and active reactor sites. Such a policy would also “free up” the decommissioned sites for economic redevelopment, which can be especially attractive since such sites were originally chosen to have access to water, transportation, and the electrical grid.

The Private Fuel Storage Company (PFS), a utility consortium, designed and licensed an ISFSI in Utah that has not been built. PFS has updated its cost for a centralized facility in 2009 dollars to indicate that the cost of an ISFSI is $118 Million assuming it is operated as a federal facility with no taxes paid. The cost of the rail infrastructure for the PFS, including transport casks and all handling equipment, is estimated to be $53 Million plus an additional rail extension to the site of $34 Million. Dedicated trains are assumed with 3 casks per train assumed in the analysis. Annual operating expenses for loading and unloading casks are approximately the same at $8.8 million. The PFS numbers do not include the costs of the waste canisters or storage overpacks which are assumed to be shipped to the site from the reactors.

The rail infrastructure costs are considerably different at $53.2 million compared to Electric Power Research Institute estimate of $366 million due largely to a smaller number of locomotives needed (4 vs. 14) and associated cask shipping cars for the same 2000 MTU per year of shipments to the interim storage site. PFS calculates the cost to ship 3 casks per train to be $75 per mile with dedicated trains. The PFS numbers shown reflect actual cost estimates for their project in Utah. Reconciliation of these numbers with EPRI cost assumptions is difficult but some obvious differences are that EPRI assumes only two casks per train and a site that has considerably higher capital cost for construction compared to what PFS expects.
For decommissioned sites, our economic modeling of the net present value—comparing at-reactor storage with centralized storage at a number of reference locations in the east, west and mid-west—show significant advantages for consolidation at centralized sites. This is due largely to the cessation of government payments for spent fuel storage at shutdown sites once cleared of spent fuel. A second important result is the relative indifference of costs to site location despite the significant real distance between sites. Transportation costs are not a major cost driver. This implies that policy makers have wide flexibility in siting a central facility, a flexibility that should come in handy considering past experience.

A higher degree of confidence is required in the accuracy of the cost parameters used for transportation costs and O&M costs at active sites. If transportation costs are sufficiently low, and O&M costs sufficiently high, it would be cost-advantageous to consolidate SNF from active sites. Our analysis preliminarily supports this finding. This would create a regular stream of SNF to be consolidated, and in turn improve the relative costs of dedicated transport. The dedicated train scenarios do show that the use of dedicated trains can be advantageous in terms of lowering the overall costs of management of spent fuel in interim storage from all sites since it more effectively utilizes the dedicated train capacity.

It should be noted however, that when the sunk costs of existing at reactor ISFSI’s are included in the overall cost of constructing and operating new central storage facilities, it is cheaper to keep the spent fuel at the active reactor sites. Many of the costs of spent fuel storage, such as security, are almost independent of the quantity of spent fuel that is stored at a site. For sites with operating reactors producing spent fuel and having existing ISFSIs, removal of some SNF has little impact on site operational costs.

The results of the assessment show that there are significant incentives today for a small centralized storage facility (~3000 tons) to address SNF from decommissioned reactor sites that would be expandable when other operating reactor sites are decommissioned, likely in the 2030 timeframe. Again this is because many of the costs associated with spent fuel storage are nearly independent of the quantity of spent fuel being stored. If centralized storage was built and available, some utilities at sites with operating reactors might choose to ship SNF to such a facility while many utilities might choose to store SNF for appropriate payments of sunk storage costs while the reactor sites had operating reactors.

Despite the lower system costs of maintaining on-site storage for currently operating reactors, it may be desirable for other reasons to start moving SNF from operating reactor sites (but with priority still afforded to decommissioned reactors): public acceptance; facilitating new reactor construction in a number of states; straightforward resolution of federal liability for its failure to start moving SNF in 1998.

For new reactor sites, the economically preferred option would be shipment of SNF to centralized sites after the initial cooling period, as is done in countries such as Great Britain, France, Russia, and Sweden. A long-term SNF management strategy that contemplates both century-scale storage and the possibility of substantial new reactor construction and operation argues for moving towards centralized storage sites sooner rather than later.
SAFETY OF SNF STORAGE

While managed storage is believed to be safe for these periods, an R&D program should be devoted to confirm and extend the safe storage and transport period.

With the possible long term storage of spent fuel approaching 100 years in a combination of wet and dry storage, the technical data supporting such timelines was reviewed. The Nuclear Regulatory Commission has determined that “spent fuel generated in any reactor can be stored safely and without significant environmental impacts for at least 60 years beyond the licensed life of operation (which may include the term of a revised or renewed license) of that reactor in a combination of storage in its spent fuel storage basin or at either onsite or offsite independent spent fuel storage installations—a SNF storage time exceeding 100 years. However the actual data supporting such a conclusion is limited to a physical inspection of a low burnup fuel assembly after 15 years of dry storage. High burnup fuels currently used and that are in storage have not been inspected to determine whether their behavior in storage will be similar to low burnup spent fuel. Assuming that the integrity of the storage canisters is not breached allowing for air ingress, storage for long periods should be possible despite continuing degradation mechanisms due to the reduction over time of the temperature of the spent fuel. Presently, NRC licenses dry cask storage installations for 20 years but has recently changed its rule (effective May 17, 2011) to allow for initial 40 year storage periods with 40 year renewals provided that sufficient technical information is available to justify such long storage periods.

While the technical justification of long term dry cask storage may be established, additional technical justification will be needed to assure that spent fuel integrity (suitable for subsequent handling and transport) are met and that the integrity of the canisters can be maintained. Confirmatory research involving spent fuel inspections of high burnup fuel in dry casks and more extensive degradation modeling to provide adequate justification for expected periods of storage of the order of 100 years or more should be supported.

SITING OF CENTRALIZED STORAGE FACILITIES

Strong non-economic arguments can be made for building a centralized interim storage facility. These include addressing the public concern about new plant construction and associated long term nuclear waste storage at plant sites, demonstrating the spent fuel can be safely transported, setting the stage for ultimately clearing out all sites either to a reprocessing plant or a repository. These are in addition to addressing the stranded nuclear waste at fully decommissioned nuclear plants. All are seen as important public confidence building initiatives to support the continued use of nuclear energy.

The siting of a centralized regional interim storage facility will be difficult—partly because of a legacy of previous waste management programs. Past volunteer efforts authorized by Congress with the creation of the Nuclear Waste Negotiator to site a Monitored Retrievable Storage facility failed due in part to political opposition and congressional political interference in the process once decisions were near. There are no indications that there are any fundamental changes either in the politics of siting interim facilities or the willingness of states and local communities to accept such a facility. Some suggest that co-locating a reprocessing plant, collocation of nuclear R&D infrastructure, and an interim storage facility
with its attractiveness of jobs and economic stimulus might be a differentiator today, but that remains to be seen.

An option to address the decommissioned plants is to co-locate decommissioned SNF at an existing decommissioned plant ISFSI in a community willing to host spent fuel from other plants or at an active reactor site. The chances of succeeding in this effort are unknown but depend on the willingness of the community and state to accept such a solution. This might be a first near-term test of the concept of finding volunteer sites in a community that understands the real meaning of spent fuel storage and past nuclear operations. Overseas most centralized storage facilities are located at existing nuclear sites.

The Nuclear Waste Policy Act, as Amended in 1987, severely restricts the Department of Energy from building an interim waste storage facility until Yucca Mountain obtains an operating license. This legislative restriction needs to be removed to allow the construction of such a facility independent of the progress on a repository site. Private utility efforts at building a regional interim storage facility such as the Private Fuel Storage (PFS) project have also been stymied by national and state political opposition despite being granted a Nuclear Regulatory Commission license to build and operate such a facility after a 10-year licensing process.

If a volunteer site is found, the licensing process could last 10 years with another 3 to 5 years for construction before spent fuel could be accepted by the facility. Also needed is the establishment of a transportation infrastructure to ship the spent fuel casks to the facility, which could be done concurrently. This process could be expedited if existing federal facilities that have the requisite land, security and infrastructure could be used. Since the PFS site already has an NRC license, time would be saved if that site proved to be politically viable.

CONCLUSIONS

Planning for long term managed storage of spent nuclear fuel—for about a century—should be an integral part of nuclear fuel cycle design. Long-term managed storage preserves future options for SNF utilization at little relative cost. Maintaining options is important because resolution of major uncertainties over time will determine whether LWR SNF is to be considered a waste destined for direct geological disposal or a valuable fuel resource for a future closed fuel cycle.

Preservation of options for future fuel cycle choices has been undervalued in the debate about fuel cycle policy. Managed storage can be done safely at operating reactor sites, centralized storage facilities or geological repositories designed for retrievability (an alternative form of centralized storage). While managed storage is believed to be safe for these periods, an R&D program should be devoted to confirm and extend the safe storage and transport period.

The possibility of storage for a century, which is longer than the anticipated operating lifetimes of nuclear reactors, suggests that the United States should move toward centralized SNF storage sites—starting with SNF from decommissioned reactor sites and in support of a long-term SNF management strategy.
These broad recommendations lead to specific recommended actions. Remove SNF from decommissioned reactor sites to a secure national facility that has the infrastructure to support long term storage. The PFS experience has demonstrated the licenseability of a consolidated storage site. If a policy decision is made on recycling, collocate interim storage, reprocessing, and fuel fabrication (with recycled fissionable materials) facilities. This would minimize future storage and transportation costs and minimize proliferation risks. Legislation should be introduced to remove the linkage between the repository and the construction of an interim storage facility. Spent fuel retrievability should be considered for any repository to preserve options.

CITATIONS AND NOTES

2. www.skbe.se
4. www.andra.fr/international/index.html
8. There have been only limited shipments in the U.S. in recent decades of SNF. However, the U.S. navy regularly ships SNF from nuclear navy maintenance facilities to storage facilities in Idaho. Overseas (France, Great Britain, Sweden, Japan, etc.) there is a massive experience base in shipping commercial SNF. European experience with SNF shipment is roughly equivalent to that required to fill a repository of the size of Yucca Mountain (See Going the Distance, The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States, National Research Council (2006), Table 3.5)
12. There are large technical, economic, and non-proliferation incentives to collocate reprocessing and recycle fuel fabrication facilities at either interim SNF storage sites or at the repository site (Chapter 5). The traditional vision of the fuel cycle with separately sited storage, reprocessing, fuel fabrication, and repository facilities is an accident of history that resulted from the sequence of development of early nuclear fuel cycle facilities associated with national security.