An Evaluation of Alternative Waste Management System Architectures – 16338

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ABSTRACT

The Nuclear Fuels Storage and Transportation Planning Project (NFST), under the U.S. Department of Energy, Office of Nuclear Energy, Office of Fuel Cycle Technologies, is conducting analyses to inform future decisions regarding an integrated waste management system with a current focus on commercial spent nuclear fuel (SNF). This work builds on results from previous systems architecture studies within NFST. System-level analyses of the overall interface between at-reactor, consolidated storage, and ultimate disposition, along with the development of supporting logistic simulation tools, were initiated in 2012. This paper highlights recent results of the NFST systems architecture analysis efforts initiated in 2012. Waste management design choices are evaluated with respect to the impact on the entire system. This includes an analysis of alternative strategies for allocating receipt of SNF from reactor sites, storage options for SNF at an interim storage facility (ISF), and thermal limits restricting the transportation of canisters from an ISF to a mined geological repository (MGR).

INTRODUCTION

The Nuclear Fuels Storage and Transportation Planning Project (NFST), under the U.S. Department of Energy, Office of Nuclear Energy, Office of Fuel Cycle Technologies, is conducting analyses to inform future decisions regarding the waste management system. Spent nuclear fuel (SNF) management system analysis, system engineering, and decision analysis principles are being used to inform future decisions regarding an integrated used fuel management system. The application of these techniques to this complex and challenging problem have been recognized as being essential by the Blue Ribbon Commission for America’s Nuclear Future and the U.S. Nuclear Waste Technical Review Board.

This work builds on results from previous NFST Systems Architecture studies [1, 2, and 3]. System-level analyses of the overall interface between at-reactor, consolidated storage, and ultimate disposition, along with the development of supporting logistic simulation tools, were initiated in 2012. The objectives of the initial effort [1] were two-fold: 1) to develop methodologies, approaches, and tools (capability development), and 2) to evaluate select SNF disposition scenarios (capability demonstration).

This paper highlights recent results of the NFST Systems Architecture analysis efforts initiated in 2012. Recent activities have built on prior work and continue the development of methodologies, approaches and tools. Additionally, the suite of SNF disposition scenarios were broadened and evaluated based on the insights gained and recommendations made in previous efforts. Various alternatives for managing SNF generated from the light water reactors in the U.S. are evaluated. Specifically, this paper discusses:

- quantitative information with respect to a broad range of SNF management alternatives and considerations
- impacts of storage choices on SNF storage, handling, and disposal options
- alternative strategies and an evaluation of those strategies with respect to various metrics and performance measures
- a broad range of factors including repository emplacement capability, thermal constraints, re-packaging needs, storage and transportation alternatives, and impacts on utility operations

The scenarios chosen for evaluation and the assumptions, inputs, and boundary conditions selected for initial analyses were designed to gain insight regarding integrated system dynamics and trends. These initial analyses also pointed to where additional system architecture analyses should focus.

Studies conducted in 2013 [2] and 2014 [3] built on the previous work and continued the development of methodologies, approaches and tools, and broadened the suite of SNF disposition scenarios that were evaluated based on the insights gained by each prior effort.

Activities continued in 2015 and the results and insights gained are highlighted in this paper. The insights and recommendations reported herein should not be seen as replacing those previously made, but rather augmenting them to provide improved understanding of how a SNF management system could be deployed and operated, and to provide recommendations for future work activities.

The analyses and evaluations discussed pertain only to the deployment and operation of a larger interim storage facility (ISF) and not to a pilot ISF or a geologic repository as described in the Administration's *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* (hereafter referred to as the "Administration's *Strategy*") [4]. However, assumptions, inputs, and potential interface constraints with respect to an ISF and geologic repository are considered. For example, the Administration's Strategy establishes a reference for facility operations start dates that were used in the evaluations.

This is a technical report that does not take into account the contractual limitations under the Standard Contract. Under the provisions of the Standard Contract, DOE does not consider SNF in canisters to be an acceptable waste form, absent a mutually agreed to contract modification. To ensure the ability to transfer SNF to the government under the Standard Contract, the individual spent fuel assemblies must be retrievable for packaging into a DOE-supplied transportation cask.

DESCRIPTION OF METHODS AND RESULTS

The analyses in this report involve comparisons between scenarios that represent different potential integrated waste management system architectures. These scenarios typically differ in a few key characteristics in order to isolate and identify the impact of those differences on the performance of the integrated system. In order to provide a central point of comparison for these scenario comparisons, a single scenario is defined and is frequently referenced throughout this report as simply "the reference scenario." This scenario is not considered to be a policy decision or the most likely scenario; instead, it is the base (or reference) case for all analyses in this paper.

The Transportation Storage Logistics (TSL) simulation tool is used to simulate all scenarios in this report including the reference scenario. The TSL simulation tool couples the legacy Civilian Radioactive Waste Management System (CRWMS) Analysis and Logistics Visually Interactive model (CALVIN) and Transportation Operations Model (TOM) into a framework for evaluating the entire system for managing commercial SNF, DOE owned spent nuclear fuel, and DOE owned high level nuclear waste. The focus of this report is largely on those elements of the waste management system for commercial SNF modeled in the CALVIN portion of TSL. For that reason, and ease of reference, the acronym "CALVIN" is used in this report to refer to the simulation model.

Reference Scenario

The details and assumptions of the Fiscal Year 2015 (FY15) reference scenario relevant to the content in this paper are included below.

<u>Reactor Assumptions</u>

1. The inventory of SNF at reactors will continue to accumulate as those reactors discharge SNF. All SNF will continue to be loaded into the dry storage systems currently being used (as of June 2014). No system-wide change to reusable bare fuel transportation casks will occur. Reactors currently loading bolted-lid cask systems will continue to load those systems, just as those reactors currently loading welded, canister-based systems will continue to load those systems.
2. All reactors are assumed to operate for 60 years with no early shutdowns, additional extensions, or new reactors coming online. The exceptions are those reactors that have already shut down, those that had announced a shutdown date prior to 2015, and SNF stored at Morris.
    a. Reactors that have already shut down: Big Rock Point, Haddam Neck, Humboldt Bay 3, La Crosse, Maine Yankee, Rancho Seco, Trojan, Yankee Rowe, Zion 1 and 2, Kewaunee, Crystal River 3, San Onofre 1, 2, and 3, Vermont Yankee, Indian Point 1, Millstone 1, Dresden 1
    b. Reactors that have announced a shutdown date: Oyster Creek

3. SNF is shipped from all reactor sites at a rate of 3000 metric tons of uranium (MTU) per year (3000 MTU/yr) once full-scale transportation begins (see ISF Assumptions below for throughput ramp-up information).
4. For the purposes of this paper, allocation priority refers to the priority in which SNF shipments are allocated to reactor sites and how much SNF is allocated to be shipped from each site in a given year; and acceptance priority refers to the priority in which SNF is provided by utilities from their reactor sites and accepted for transport by the waste management system in any year. SNF from shutdown sites (sites where all operating reactors have been shut down) is allocated and accepted first. After the shutdown sites have been de-inventoried, all SNF is allocated for pickup from a site based on an Oldest-Fuel-First (OFF) priority ranking, and is accepted from a site based on a Youngest Fuel First (YFF) priority ranking for SNF calculated to have been out of the reactor for more than five years.
5. If SNF is pulled directly from the spent fuel pool for immediate transportation (i.e., not from independent spent fuel storage installations [ISFSIs] for dry storage), the SNF will be placed in a dual-purpose canister (DPC) that will be loaded into a transportation overpack. The capacity of the canister is 37 pressurized water reactor (PWR) or 89 boiling water reactor (BWR) assemblies (vertical) or 37 PWR or 61 BWR assemblies (horizontal), and is assumed to be the same orientation (vertical or horizontal) as the system loaded at the reactor for ISFSI storage.
6. All reactor site pools are closed 5 years after the final discharge from the site's reactors. Any fuel left in the pools at that time is transferred into on-site dry storage. The fuel is placed into dry storage canisters that match the thermal limits of those canisters for storage.
7. All canisters and casks at reactors are assumed to be transportable. Specifically, any canister or cask system without a transportation certificate of compliance is assumed to receive an exemption for transport to the ISF as well as an exemption for transport from the ISF to the repository.
8. No repackaging of SNF occurs at reactor sites.

<u>Interim Storage Facility Assumptions</u>

1. Pilot ISF acceptance begins in 2021.
2. The Pilot ISF and full-scale ISF are co-located.
3. The full-scale ISF begins operations in 2025, with identical operations (acceptance, canister type, storage type, etc.) to the pilot ISF.
4. Shutdown sites (as of January 1, 2015) are given priority, as noted in reactor assumption 4.
5. The annual acceptance rate of SNF begins at 500 MTU/yr in 2021 and increases each year by 500 MTU/yr until it reaches its maximum rate of 3000 MTU/yr in 2026.
6. All SNF is placed in the currently used storage and transportation systems before it reaches the ISF, and no bare fuel acceptance, storage, packaging, or repackaging occurs at the ISF.

7. All SNF is stored in the same storage structures (vertical overpacks or horizontal storage modules) as those at the reactor ISFSIs.
8. All SNF passes through the ISF before being sent to the repository. That is, SNF from reactor sites is always sent to the ISF even once the MGR has begun operation. There is no direct transport from the reactor sites to the MGR. As a consequence, all shipments of SNF arriving at the MGR initiate at the ISF.

Repository Assumptions

1. The repository begins accepting 3000 MTU/yr of SNF beginning in 2048.
2. SNF is only received from the ISF (not directly from reactors).
3. All SNF will be repackaged at the repository into purpose-built, repository-specific waste packages.
4. Waste package size is assumed to be 12 PWR assemblies or 32 BWR assemblies, with a maximum heat load of 5.5 kW.

One assumption of the reference scenario that is frequently altered throughout this is the assumption that all fuel transported directly from spent fuel pools at reactor sites are transported in DPCs. In many of the scenarios studied below, SNF transported directly from the spent fuel pools is done so in reusable bare fuel transportation casks. Such a change in assumption will be noted whenever these “bare fuel” casks are used.

At-Reactor Acceptance Strategy Analysis

A key aspect of the analysis of integrated waste management system architecture scenarios is the assumption about the allocation priority for the shipment of SNF available from the reactors. The previous analyses [1-3] indicated that allocation and acceptance priority assumptions have a significant impact on the SNF management system and that alternative allocation/acceptance priorities should be examined in addition to the oldest-fuel-first (OFF) priority often considered in waste management system analyses. These analyses also pointed out that thermal considerations can have a major impact on the operation of the system. Because thermal constraints on transportation overpacks/casks can be more stringent than the constraints on storage canisters, loading fuel into very large storage canisters at reactor sites may require storage of those canisters for decades before they have cooled enough to meet the thermal limits for transportation. These thermal constraints are taken into account in the evaluation of alternative SNF allocation/acceptance strategies.

It should be noted that the ability to ship transportation casks might be limited by external radiation dose limits specified by 10 CFR Part 71 rather than by thermal limits. The thermal limits for SNF bare fuel casks are not set based on meeting dose rate criteria but are set so as to ensure safety margin based on the temperature limits of contents and package components. While the SNF heat loads in a SNF canister/cask may be correlated to higher dose rates, the relationship is complicated and depends on where the dose rate is measured or calculated. Transportation cask safety analysis reports do not claim that meeting the heat load limit ensures meeting dose rate limits.

The potential impacts of dose rate limits have been investigated in previous analysis [2].

This section provides results of an evaluation of alternative allocation priority strategies, building on previous studies [3]. The scenarios in this evaluation are variations on the FY15 reference scenario discussed above. Variants in this section are scenarios with acceptance rates of 4500 MTU/yr, increased from the 3000 MTU/yr prescribed by the reference scenario. Additionally, three alternative allocation priority strategies are compared to the OFF strategy prescribed by the reference scenario. The alternative allocation strategies are:

<u>Oldest Fuel First (OFF)</u>
This allocation strategy is consistent with the reference scenario and the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (10 CFR 961).

<u>Prioritize eliminating additional dry storage and clearing shutdown sites (DS-SD)</u>
This strategy first eliminates the need for fuel to be placed in new dry storage containers at reactor sites while the reactor is in operation. Once new dry storage is prevented, the remaining MTU left to be allocated are allocated to reactor sites in the order of those sites' projected shutdown date.

<u>Accept SNF post-shutdown and prioritize clearing shutdown sites (P-SD)</u>
This strategy only accepts fuel from sites at which all reactors have shut down. Additionally, this strategy prioritizes sites in the order in which they have shut down.

<u>Prioritize according to shutdown order, accept SNF 5 years prior to shutdown, and prioritize clearing sites 5 years after shutdown (SD-10yr)</u>
This strategy's first priority is to clear the sites in the order in which the sites shut down. In doing so, SNF is collected from sites starting 5 years prior to the sites' projected shutdown dates and no sooner. Finally, the goal is to clear the sites within 5 years of shutdown, ideally leaving a 10-year window in which SNF is cleared from each site. It is worth noting that restrictions on acceptance rate and constraints at the reactor sites prevent all sites from being cleared within this window.

Variations on the reference scenario are used in evaluating the alternative allocation strategies. Two methods for transporting SNF (canisters only, and canisters with reusable bare fuel casks), two acceptance rates (3000 MTU/yr and 4500 MTU/yr), and the four allocation strategies listed above are used. A complete list of scenarios compared in this study is listed in Table I. This table also includes a "key" for each scenario to be used as shorthand in referencing.

TABLE I: Scenarios for evaluating alternative SNF allocation strategies

SNF Acceptance Approach	SNF Acceptance Rate	Allocation Strategy	Key
Canisters Only	3000 MTU/yr	OFF	Cans 3000 OFF*
		DS-SD	Cans 3000 DS-SD
		P-SD	Cans 3000 P-SD
		SD-10yr	Cans 3000 SD-10yr
	4500 MTU/yr	OFF	Cans 4500 OFF
		DS-SD	Cans 4500 DS-SD
		P-SD	Cans 4500 P-SD
		SD-10yr	Cans 4500 SD-10yr
Canisters and Bare Fuel Casks	3000 MTU/yr	OFF	CansBare 3000 OFF
		DS-SD	CansBare 3000 DS-SD
		P-SD	CansBare 3000 P-SD
		SD-10yr	CansBare 3000 SD-10yr
	4500 MTU/yr	OFF	CansBare 4500 OFF
		DS-SD	CansBare 4500 DS-SD
		P-SD	CansBare 4500 P-SD
		SD-10yr	CansBare 4500 SD-10yr

*reference scenario

Figures 1 and Figure 2 show the CALVIN simulation results for the different scenarios listed in Table I. These figures show the number of shutdown reactor sites with SNF still remaining on-site each year. Figure 1 shows results for scenarios that ship all SNF from sites in canisters. Figure 2 shows results for scenarios that transport fuel directly from the pools in reusable bare fuel transportation casks, which can ship assemblies with higher decay-heat thermal output. Additionally, the darker curves indicate scenarios with acceptance rates of 3000 MTU/yr. The lighter curves indicate those scenarios with acceptance rates of 4500 MTU/yr.

Notice that in the canisters-only scenarios (blue curves), increasing the acceptance rate from 3000 MTU/yr to 4500 MTU/yr while still using the OFF allocation strategy has a significant impact on clearing SNF from the reactor sites. The other allocation strategies yield marginal impacts as compared to the 4500 MTU/yr OFF allocation strategy. Alternatively, in the canisters and bare fuel casks scenarios (red curves), the combination of increased acceptance rate and alternative allocation strategies has a significant impact relative to using OFF.

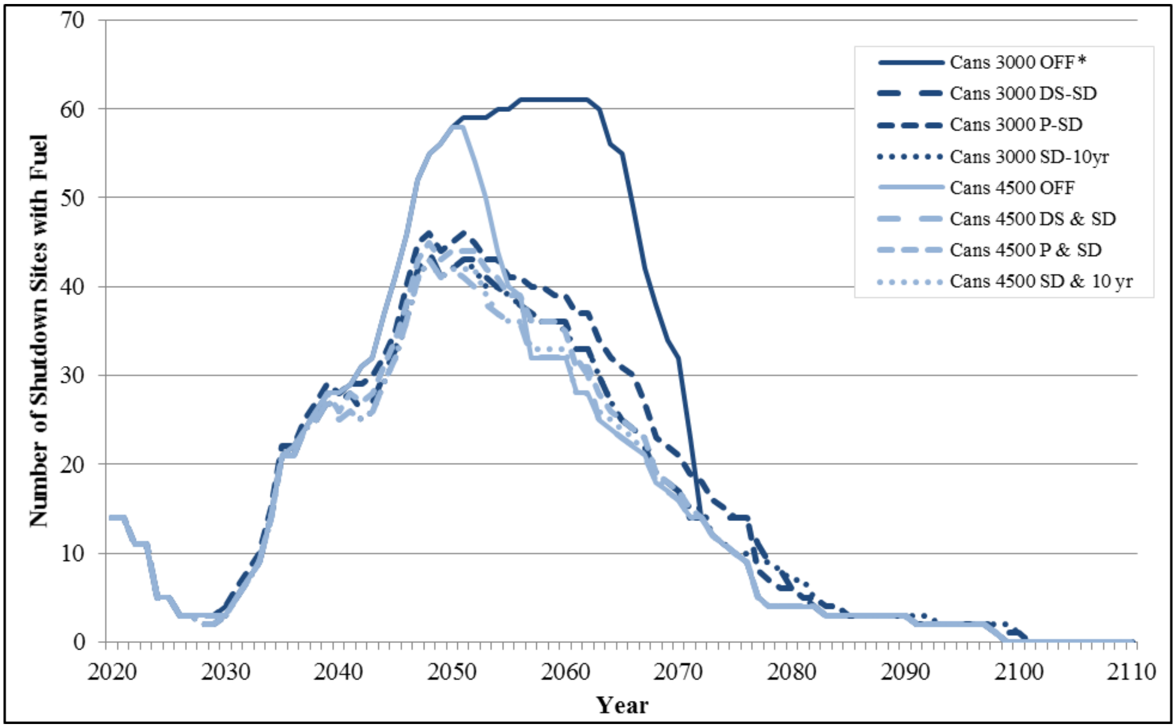


Fig. 1. Number of shutdown sites with SNF remaining on-site (canisters-only scenarios)

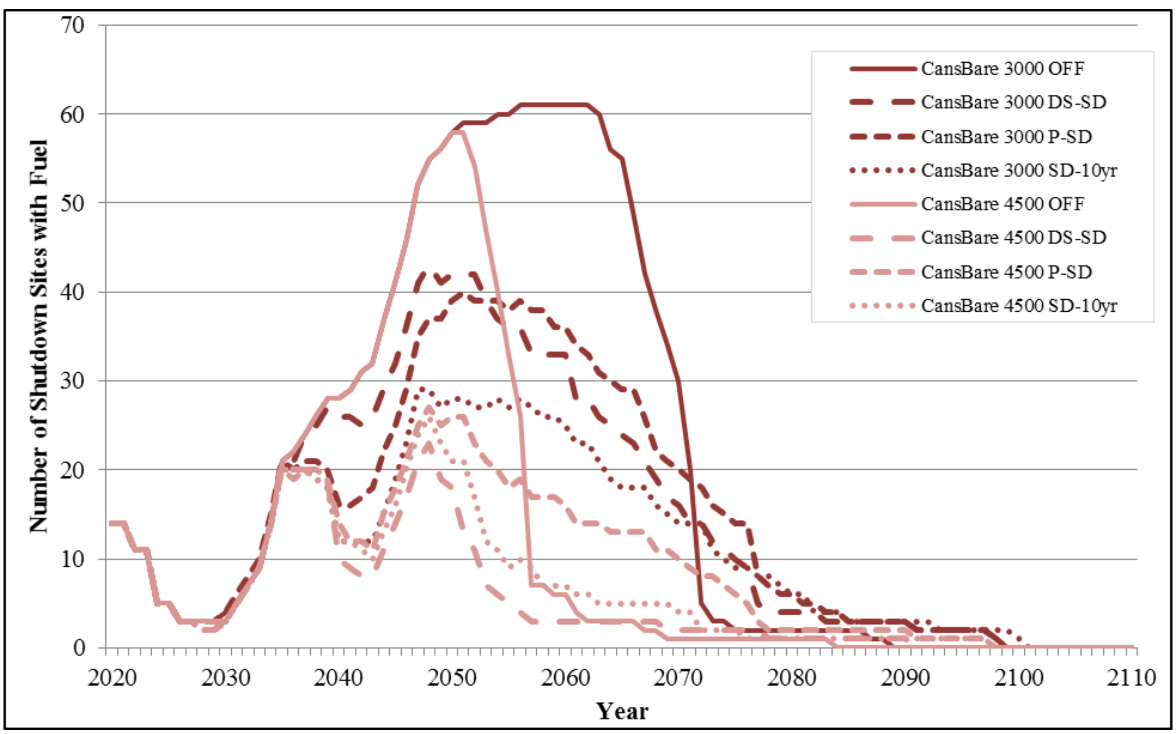


Fig. 2. Number of shutdown sites with SNF remaining on-site (canisters and bare fuel casks scenarios)

The area under each curve in Figure 1 and Figure 2 represents the total years with SNF on each reactor site integrated over all sites. This is a measure of both the post-shutdown storage cost for the site (since the ISFSI must be maintained as long as there is any SNF on the site) and the community impact (since the site cannot be repurposed until SNF removal is complete and the ISFSI is decommissioned). The total number of years with SNF on-site is summed over all sites (fuel-on-site years) and is shown in and Table II.

TABLE II. Total number of site years with SNF on reactor sites (fuel-on-site years) following reactor shutdown, with percentage improvement over OFF

Acceptance Rate	**3000 MTU/yr**				**4500 MTU/yr**			
Allocation Strategy	**OFF***	**DS -SD**	**P -SD**	**SD -10yr**	**OFF**	**DS -SD**	**P -SD**	**SD -10yr**
Canisters Only	1930	1410	1528	1392	1465	1310	1386	1318
Improvement over OFF		27%	21%	28%		11%	5%	10%
Canisters with Bare Fuel	1842	1257	1340	1030	1018	478	813	588
Improvement over OFF		32%	27%	44%		53%	20%	42%

*FY15 reference scenario

When only canisters are used, all allocation strategy alternatives reduce the fuel-on-site years compared to the 3000 MTU/yr OFF strategy reference scenario (Cans 3000 MTU/yr OFF). However the alternative strategies perform similarly to one another with a 20% to 30% reduction in site years over the reference scenario. The use of bare fuel casks in addition to canisters reduces fuel-on-site-years by close to 9% over the 3000 MTU/yr OFF canister only reference scenario. For these cases which include bare fuel, alternative acceptance strategies reduce fuel-on-site years by between 30% and 45% as compared to the same approaches when only canisters are accepted. Strategies that increase acceptance to 4500 MTU/yr and include alternative allocation strategies further reduce fuel-on-site years.

The thermal constraints on the transportation overpacks for dry storage canisters are the drivers in the differences between those scenarios that transport all SNF in canisters and those scenarios that transport both SNF from dry storage in canisters and SNF from the spent fuel pools in reusable bare fuel transportation casks. In all of the canister only scenarios, the simulation reaches a point where canisters in dry storage are sitting at reactor sites waiting for the fuel to cool enough to be transported. This situation results in the long “tails” shown on the curves in Figure 1 and Figure 2.

These scenarios assume that five years after the last reactor on site shuts down all SNF remaining in spent fuel pools is transferred to on-site dry storage. The dry storage canisters are loaded to meet the canister storage thermal limits that will exceed the thermal limits of transportation overpacks. The canisters must then sit in on-site dry storage until the SNF assemblies have cooled enough to meet transportation overpack thermal limits. However, if the spent fuel pools remain open longer, the fuel could be transported using transportable bare fuel casks having higher thermal limits, and the site could be cleared faster.

Eight additional scenarios that allow the pools at reactor sites to stay open until all SNF has been removed from the pool were analyzed. Combinations of the four allocation strategies (OFF, DS-SD, P-SD, and SD-10yr), and two acceptance rates (3000 MTU/yr and 4500 MTU/yr) are compared. Bare fuel casks are used to transport SNF directly from the pools in all scenarios. The impact on site years for the two pool closure practices is shown in Table III.

TABLE III. Post-shutdown site-years with fuel on-site for scenarios evaluating the practice of pool closure post reactor shutdown.

	Post-Shutdown Spent Fuel Pool Management		**Difference in Site-Years**	
	Pools closed 5 years post shutdown	**Pools remain open until all SNF removed**	**Absolute**	**Relative**
3000 CansBare OFF	1842	1821	21	1%
3000 CansBare DS-SD	1257	859	398	32%
3000 CansBare P-SD	1340	1071	269	20%
3000 CansBare SD-10yr	1030	764	266	26%
4500 CansBare OFF	1018	971	47	5%
4500 CansBare DS-SD	478	432	46	10%
4500 CansBare P-SD	813	672	141	17%
4500 CansBare SD-10yr	588	526	62	11%

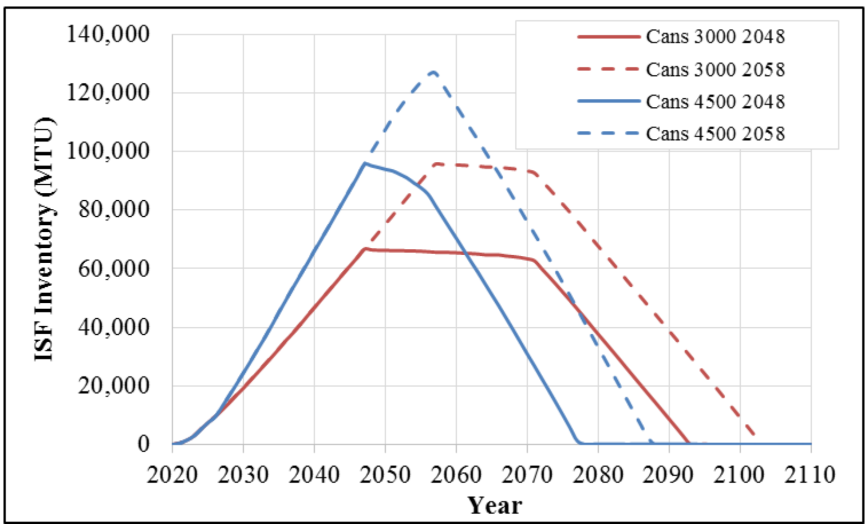
Assuming that the spent fuel pools remain open after reactor shutdown significantly reduces the site years for acceptance strategy alternatives as compared to an OFF acceptance strategy. In the 3000 MTU/yr scenarios, leaving the pools open reduces site years by 20%-32% for the alternative allocation strategies. The 4500 MTU/yr cases see less of a reduction (10%-17%), due largely to the fact that those scenarios clear sites of SNF the fastest.

Keeping the pools open longer to permit increased access to individual assemblies reduces the number of site years with SNF remaining on site. However, this improvement comes at an increased cost required for maintaining an operational spent fuel pool longer than would be necessary if the SNF were transferred to dry storage and the pools were closed. Rough order of magnitude cost estimates indicate that total at-reactor costs may be up to 67% larger in the cases where the spent fuel pools remain open.

Interim Storage Facility Inventory

The various SNF acceptance scenarios have an effect on the ISF inventory. All DPCs arriving at the ISF were assumed to be placed in dry storage. SNF arriving at the ISF in reusable bare fuel transportation casks can be placed either into DPCs upon receipt at the ISF or stored in a bare fuel storage facility (such as a spent fuel pool).

The SNF inventory at the ISF depends on the rate that SNF is accepted from the reactor fleet, when shipments to a repository begin, and the rate of SNF shipment to the repository. This dependency is shown in Figure 3 for scenarios where all SNF is shipped from the reactors in DPCs, stored at the ISF, and then transported to a repository. Scenarios where SNF is transported from the reactor spent fuel pools in reusable bare fuel transportation casks yield similar total inventory results.

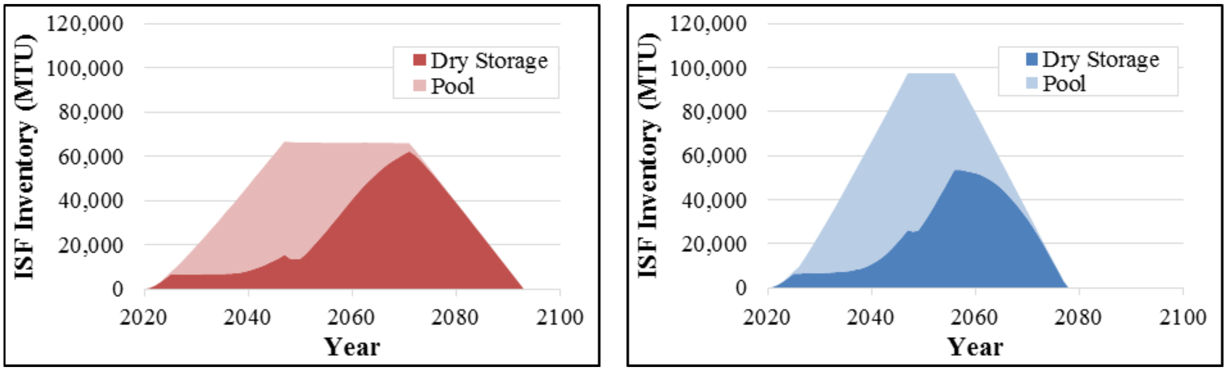


Notes: ISF and repository acceptance rates of 3000 MTU/yr and 4500 MTU/yr; Repository operational dates of 2048 and 205.

Fig. 3. ISF inventory (MTU) for Alternative Acceptance Rates and Repository Start Dates

Additional scenarios examined the impact of different storage options for bare fuel on ISF inventory when bare fuel casks are used to transport SNF from the spent fuel pools at reactor sites to the ISF. Two acceptance rates were evaluated, with fuel arriving at both the ISF and the MGR at a rate of either 3000 MTU/yr or 4500 MTU/yr. Two options for storing arriving bare fuel at the ISF were also examined (bare fuel loaded into DPC or placed into a spent fuel pool). All other details of the reference scenario, such as the use of the OFF allocation strategy, remain unchanged.

When bare fuel arriving at the ISF is loaded into DPCs, the peak inventory is 65,503 MTU and 95,479 MTU for acceptance rates of 3000 MTU/yr and 4500 MTU/yr, respectively (all contained in DPCs). When bare fuel arriving at the ISF is placed in the spent fuel pool there is a mix of fuel in dry and pool storage that changes over time, as shown in Figure 4. This is a result of the preference assumed in the analyses to ship SNF from the reactor spent fuel pools over that from dry storage.



3000 MTU/yr ISF and Repository Acceptance Rate **4500 MTU/yr ISF and Repository Acceptance Rate**

Fig. 4. SNF Inventory at an ISF for DPC and Bare Fuel Storage

The results shown in Figure 4 demonstrate that the configuration of an ISF, when certain capabilities and capacities would be needed, differs for each of the scenarios analyzed. This would also affect the facility cost (both annual and total costs). A relative comparison of the rough order of magnitude (ROM) total lifecycle cost estimates for the ISF for scenarios analyzed where bare fuel arrives at the ISF are provided in Figure 5. The figure displays ROM lifecycle costs as a percentage of the total ROM estimate for the reference scenario (3000 Dry). ISF dry storage costs include the cost of the storage pads/modules and the cost of DPCs used for the storage of arriving bare fuel. Facility costs include all other costs associated with the ISF and are identical in these scenarios, except for the number of bare fuel receipt bays and pool storage modules required. The operational costs include canister and bare fuel handling crews, utility costs, and materials and contracts costs.

Packaging SNF from bare fuel shipments into DPCs ("Dry" scenarios) increases the ISF dry storage costs because of the need to acquire new DPCs. Conversely, storing SNF from bare fuel shipments in spent fuel pools requires the construction of pool storage capacity, thus increasing the facility costs. Finally, an increase in the acceptance rate (from 3000 MTU/yr to 4500 MTU/yr) requires an increase in the number of receipt bays and fuel handling or canister lines.

With an acceptance rate of 3000 MTU/yr, the increased costs due to pool storage are roughly evened out by the increased cost of dry storage. The total cost of storing SNF in pools at the ISF is essentially the same as for packaging the SNF into canisters upon arrival at the ISF. In the 4500 MTU/yr scenarios, canister storage of bare fuel arriving at the ISF is estimated to be roughly 8% more than for storing the bare fuel in a pool.

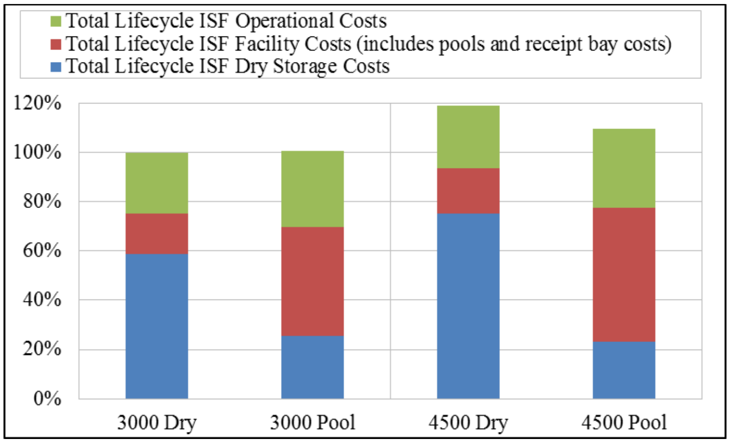


Fig. 5. Relative comparison of ROM total lifecycle cost estimates at ISF for alternative storage methods

Repository Thermal Limits and ISF Capacity

Shipments from the ISF to a mined geologic repository (MGR) could be managed to ensure that all SNF assemblies arriving at a MGR would be sufficiently cool to be placed into waste packages that meet emplacement thermal limits. This could preclude having to store SNF at the repository until it further cools. Linking MGR emplacement thermal to shipments from the ISF can impact ISF inventory and how long an ISF would have to remain in operation.

These impacts were evaluated for two repository receipt rates (3000 MTU/yr and 4500 MTU/yr) and assuming four media dependent emplacement thermal limits and waste package sizes:

- Clay closed or granite closed: 1,700 W; 4 PWR/9 BWR assembly waste package
- Salt closed: 5,500 W; 12 PWR/32 BWR assembly waste package
- Open mode: 18,000 W; 21 PWR/44 BWR assembly waste package

The enclosed modes involve emplacing packages directly into contact with engineered material or host rock with temperature limits. The open modes maintain air space around each package that can be ventilated to remove heat prior to permanent closure of the repository [5]. For ease of notation the clay closed and granite closed scenarios are evaluated together as they are assumed to have the same thermal limits for this analysis and are simply referred to as “clay.” The salt closed scenarios will simply be referred to as “salt” scenarios.

This evaluation considered an ISF configuration where all SNF was stored in dry storage canisters. Canisters were transported from the ISF to the MGR once the average assembly heat for each canister is below the repository emplacement thermal limit divided by the waste package capacity. The assemblies were then repackaged into disposable canisters.

Figure 5 shows the ISF inventory over time for each of the six scenarios considered. The results show that the thermal limits of the open mode MGR concept allow for the fastest reduction of ISF inventory since those thermal limits are the least restrictive. Notably, the acceptance rate has an effect on the peak inventory level at the ISF, but does not affect the date of the final shipment from the ISF. Late in the simulation, inventories of the 3000 MTU/yr and 4500 MTU/yr scenarios start to align as the inventory is driven by the thermal limits of the remaining canisters that contain younger and hotter SNF assemblies. Regardless of acceptance rate, the analysis results show that the ISF remains open for 72 years for open media, 101 years for salt, and 108 years for clay and granite to allow all SNF being stored at the ISF to cool sufficiently for shipment.

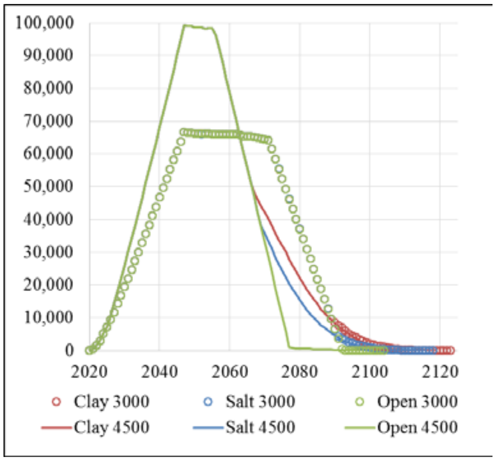


Fig. 6. ISF inventory over time for alternative MGR thermal limits and acceptance rates

CONCLUSIONS

The analyses described in this report provide a number of relevant conclusions regarding the waste management system.

- Alternative allocation strategies could lead to significant benefits with respect to at-reactor management logistics and costs. Alternative strategies may allow SNF to be cleared from reactor sites more efficiently than under the OFF allocation. Combining these alternative strategies with increased acceptance rates (i.e., 4500 MTU/yr instead of 3000 MTU/yr) shows even greater benefits in at-reactor logistics and costs.
- The use of bare fuel casks along with alternative allocation strategies, and accelerated acceptance rates could increase the rate that SNF could be cleared from the reactor sites, but would require bare fuel handling capabilities at the ISF.
- Leaving the spent fuel pools open after reactor sites shut down could also expedite the clearing of SNF from the reactor sites. This improvement, however, would require continual operation of the spent fuel pools after the reactors shut down, increasing at-reactor SNF management costs.

- A large capacity bare fuel storage capability would be needed at the ISF if bare fuel is accepted from reactor site pools. This capability could be avoided by packaging bare fuel in dry storage canisters upon arrival at the ISF.
- Pool storage at the ISF would not be cost-prohibitive when compared to dry storage of all SNF at the ISF. Total costs for bare fuel storage at the ISF with a 3000 MTU/yr acceptance rate would be essentially the same those for dry storage, but are lower for a 4500 MTU/yr acceptance rate. This finding is in contrast to previous studies and is based on more up-to-date cost information provided by industry input and more detailed ISF design studies. However, as these estimates are a work in progress, these observations should be considered preliminary. Design concept development, including more detailed cost information should continue regarding all aspects of ISF designs and storage configurations to further refine results.
- The acceptance rate from reactor sites would have a significant impact on inventory levels at the ISF. An acceptance rate of 4500 MTU/yr is anticipated to require an ISF with 46% more storage capacity compared to a waste management system with an acceptance rate of 3000 MTU/yr.
- The ISF operational time would be affected by the repository media assuming that repository thermal restrictions would constrain SNF shipments between the ISF and the MGR. Specifically, the ISF would be required to remain operational for 72 years for open media thermal constraints, 101 years for an MGR in salt, and 108 years for an MGR in clay or granite.

REFERENCES

1. W.M. NUTT, R. HOWARD, I. BUSCH, J. CARTER, A. DELLEY, P. RODWELL, E. HARDIN, E. KALININA, T. COTTON, Used Fuel Management System Architecture and Interface Analyses, Proceedings of the International High-Level Radioactive Waste Management Conference, April 2013, Albuquerque, NM.
2. W. NUTT, E. MORRIS, F. PUIG, R. HOWARD, J. JARRELL, R. JOSEPH, T. COTTON, “Waste Management System Architecture Evaluations,” Proceedings of the WM2014 Conference, March 2014, Phoenix, AZ.
3. W. NUTT, C. TRAIL, T. COTTON, R. HOWARD, B. VAN DEN AKKER, “Waste Management System Architecture Evaluations,” Proceedings of the International High-Level Radioactive Waste Management Conference, April 2015, Charleston, SC.
4. U.S. DEPARTMENT OF ENERGY, “Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste,” January 2013.
5. E. HARDIN, T. HADGU, D. CLAYTON, R. HOWARD, H. GREENBERG, J. BLINK, M. SHARMA, M. SUTTON, J. CARTER, M. DUPONT AND P. RODWELL, “Disposal Concepts/Thermal Load Management (FY11/12 Summary Report),” FCRD-USED-2012-000219, Rev.1. U.S. Department of Energy, Used Fuel Disposition R&D Campaign September 2012.

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