Waste Management System Architecture Evaluations – 14564

William Nutt *, Edgar Morris *, Francesc Puig *, Robert Howard **, Joshua Jarrell **, Robert Joseph III **, Thomas Cotton ***
* Argonne National Laboratory
** Oak Ridge National Laboratory
*** Complex Systems Group LLC

ABSTRACT

The Used Fuel Management System Architecture Evaluation effort provides the U.S. Department of Energy (DOE) and others with information regarding the various alternatives for managing used nuclear fuel (UNF) generated by the current fleet of light water reactors operating in the U.S. The objectives of the effort are to:

- Provide quantitative information with respect to a broad range of UNF management alternatives and considerations
- Develop an integrated approach to evaluating storage, transportation, and disposal options, with emphasis on flexibility
- Evaluate impacts of storage choices on UNF storage, handling, and disposal options
- Identify alternative strategies and evaluate with respect to cost and flexibility
- Consider a broad range of factors including repository emplacement capability, thermal constraints, repackaging needs, storage and transportation alternatives, and impacts on utility operations.

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 objective of the initial effort [1,2] was two-fold: 1) develop methodologies, approaches, and tools (capability development), and 2) evaluate select UNF disposition scenarios (capability demonstration).

Recent activities have built on the previous work and continued the development of methodologies, approaches and tools, broadened the suite of UNF disposition scenarios that were evaluated based on the insights gained and recommendations made in that previous effort.

Additional system-level analyses of the interfaces between at-reactor used fuel management, interim storage, and geologic disposal, along with the development of supporting logistics simulation tools, have been completed. These analyses investigated different alternatives for accepting UNF from the reactor fleet and considered the implications of thermal constraints on UNF transportation casks considering the goals in the Administration's Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste [3].

It should be noted that under the provisions of the Standard Contract given in 10 CFR 961, DOE does not consider spent fuel in canisters to be an acceptable waste form, absent a mutually agreed to contract modification. To ensure the ability to transfer the spent fuel to the government under the Standard Contract, the individual spent fuel assemblies must be retrievable for packaging into a DOE-supplied transportation cask.

INTRODUCTION

With the appropriate authorizations from Congress, the Administration's Strategy identifies three goals to implement a program over the next 10 years that [3]:

- Sites, designs and licenses, constructs and begins operations of a pilot interim storage facility by 2021 with an initial focus on accepting used nuclear fuel from shutdown reactor sites;
- Advances toward the siting and licensing of a larger interim storage facility to be available by 2025 that will have sufficient capacity to provide flexibility in the waste management system and allows for acceptance of enough used nuclear fuel to reduce expected government liabilities; and
- Makes demonstrable progress on the siting and characterization of repository sites to facilitate the availability of a geologic repository by 2048.

Analyses have been completed that evaluate the system affects of different strategies for accepting UNF from the reactor sites, considering both acceptance rates and acceptance priority. These analyses further explored the effects of thermal constraints as they apply to different strategies for accepting UNF from the reactor fleet and also evaluated potential interim storage facility capacities for different thermal constraints on geologic disposal systems.

EVALUATION APPROACH

System-level analyses of the overall interface between at-reactor, consolidated storage, and ultimate disposition were initiated in 2012 and several high-level insights and recommendations for follow-on evaluations were made [1,2]. Additional system-level analyses of the interfaces between at-reactor used fuel management, interim storage, and geologic disposal have been completed that further explored two of the key recommendations made in the previous work [1,2]. These recommendations were:

The rate that UNF is processed has a significant effect on the used fuel management system: The rate that UNF is transported between facilities, received at an interim storage facility (ISF) or a repository, and processed through a packaging/re-packaging facility affects the size of the facilities and associated infrastructure and the associated costs. Larger throughput rates result in larger facilities and higher costs. There is also a trade-off with higher acceptance rates resulting in reduced at-reactor storage requirements, but larger facilities down-stream in the waste management system.

Thermal considerations have a major impact on the operation of the system: The entire UNF management system will have thermal constraints. There are thermal limits on storage canisters, transportation overpacks/casks, and on geologic media. Thermal constraints on transportation, which are more stringent than the constraints on storage canisters, mean that loading fuel into very large storage canisters at reactor sites may require storage of those canisters for decades before they could be moved due to thermal limits on the transportation overpacks/casks. These thermal constraints become more of an issue for higher UNF acceptance rates from the reactors because the older, cooler fuel is transported from the reactor sites relatively soon after acceptance begins, leaving the hotter, younger fuel to be managed. Lower acceptance rates allow this fuel to age sufficiently so it can be transported away from the sites.

An evaluation was completed to explore alternative acceptance priority strategies, building on the results previously developed [1,2], to investigate both UNF acceptance rates from the reactors and thermal constraints on transportation casks. Specifically, this evaluation considered:

- UNF packaging/re-packaging is performed at a geologic repository.
- Two scenarios for accepting UNF from the reactor sites: transport of fuel packaged into existing size canisters only (Case 1), or transport of bare fuel in re-useable transportation casks as well as canisterized fuel (Case 2).
- A Pilot ISF begins operation in 2021, consistent with the Administration's Strategy [3]. The Pilot ISF was assumed to serve the removal of all UNF from the following sites in 4 years: Maine Yankee, Yankee Rowe, Connecticut Yankee, Humboldt Bay, Big Rock Point, Rancho Seco, Trojan, La Crosse, and Zion. At these sites a total of 7649 used nuclear fuel assemblies and a total of 2813.2 metric tons heavy metal (MTHM) of used nuclear fuel are contained in 248 storage canisters [4].
- A larger ISF begins operation in 2025, consistent with the Administration's Strategy [3]. A range of acceptance priority strategies was considered for the larger ISF.
- A geologic repository is assumed to begin operation in 2048, consistent with the Administration's Strategy [3]. A single geologic repository acceptance and emplacement rate of 3,000 MTHM per year was assumed.
- In Case 1, which assumes that all fuel is transported from the reactor sites in existing size canisters, all UNF is transferred from the wet pools to dry storage, utilizing existing size canisters, five years after reactor shutdown.
- In Case 2, which assumes a combination of bare fuel and canisterized fuel is transported from the reactor sites, all UNF in the wet pools is not transferred to dry storage after reactor shutdown. UNF in the wet pools following shutdown remains there until transported off-site.

The thermal limits assumed on canister storage overpacks and canister transportation overpacks are shown in Table I. These thermal limits were obtained from 10 CFR 71 Certifications of Compliance and Safety Analysis Reports. The thermal limits assumed on re-useable bare fuel transportation casks are shown in Table II. Table I demonstrates that the thermal limits on canister transportation overpacks are much more stringent than on storage overpacks. It should be noted that designs for re-useable bare fuel rail transportation casks for use in the U.S. do not exist and the thermal limits shown in Table II are assumed. It is also assumed that re-useable transportation casks could be loaded at less than full capacity to meet cask thermal limits (sometimes referred to as de-rating). It should be noted that fully-developed re-useable bare fuel transportation casks may have higher thermal limits, perhaps on the order of 20 – 24 Kw/cask as suggested by industry representatives.

The cases evaluated using the Transportation Storage Logistics (TSL) simulator [5] consider four different UNF allocation scenarios: two oldest-fuel-first (OFF) annual allocation scenarios (3,000 MTHM/yr and 4,500 MTHM/yr) and two different approaches for site-specific allocation (SSA). In this context annual allocation determines how much UNF is allocated to be shipped from each site in a given year. It was assumed that the actual UNF selected by each utility for shipment from each site within that site's annual allocation was based on a youngest-fuel-first (YFF) principle. The amount of fuel shipped, termed acceptance, may differ from the amount allocated, primarily due to thermal constraints.

Table I. Cask/overpack thermal limits for dry storage systems

STORAGE	Transportation

Dry Storage Vendor and Package Design	Fuel Type	Canister Type	Capacity (Assemblies)	Maximum Decay Heat per Package (kW)	Maximum Decay Heat per Assembly (kW)[A]	Transportation Overpack	Maximum Decay Heat per Package (kW)	Maximum Decay Heat per Assembly (kW)[A]
Holtec HI-STORM 100[1]	PWR	MPC-24	24	34	1.417	HI-STAR 100[2]	20	0.833
	PWR	MPC-32	32	34	1.063		20	0.625
	BWR	MPC-68	68	34	0.5		18.5	0.272
Holtec HI-STORM FW[1]	PWR	MPC-37	37	47	1.27	HI-STAR 190[4]	20	0.541
	BWR	MPC-89	89	46.4	0.521		18.5	0.208
Transnuclear NUHOMS[1]	PWR	24PTH	24	40.8	1.7	MP-197 HB[2]	24	1
	PWR	32PTH1	32	40.8	1.275		24	0.75
	BWR	61BTH	61	31.2	0.511		24	0.393
NAC UMS[1]	PWR	24P	24	23	0.958	NAC UMS[2]	20	0.833
NAC MAGNASTOR[1]	PWR	37P	37	35.5	0.959	NAC MAGNATRAN[3,B]	20	0.541
	BWR	87B	87	33	0.379		20	0.23
Transnuclear TN-40[2]	PWR	Bolted	40	27	0.675	Bolted[2]	27	0.675
Transnuclear TN-32[2]	PWR	Bolted	32	32.7	1.022	Bolted[2]	32.7	1.022
Transnuclear TN-68[2]	BWR	Bolted	68	30	0.441	Bolted[2]	30	0.441

Sources:

[1]Electric Power Research Institute, Impacts Associated with Transfer of Spent Nuclear Fuel from Spent Fuel Storage Pools to Dry Storage After Five Years of Cooling, Revision 1, Report No. 1025206, August 2 2012.

[2]D.R. Leduc and J.T. Carter, Dry Storage of Used Fuel Transition to Transport, FCRD-UFD-2012-000253, August 2012 (determined from Certificates of Compliance and Safety Analysis Reports)

[3]NAC MAGNATRAN Request for CoC has been submitted to the NRC and is proprietary. Maximum decay heat per package assumed the same as the NAC UMS

[4]Thermal limits for the Holtec HI-STAR 190 are proprietary. Maximum decay heat per package assumed the same as the Holtec HI-STAR 100

Notes:

[A]As discussed in Source 1, the maximum decay heat per assembly is calculated assuming uniform loading as the package decay heat divided by the number of assemblies. The maximum decay heat per assembly under regional loading schemes will generally be higher. Package certifications of compliance and/or safety analysis reports should be used to determine specific maximum decay heat limits.

[B]Assumed NAC MAGNATRAN would be used to transport NAC MPC-26 canisters from Connecticut Yankee and MPC-36 canisters from Yankee Rowe

Table II. Re-useable bare fuel transportation cask thermal limits

Cask	Fuel Type	Maximum Decay Heat per Package (kW)	Capacity (Assemblies)	Maximum Decay Heat per Assembly (kW)
BWR 68 Assembly Rail[A]	BWR	13	68	0.191
			44	0.295
			32	0.406
PWR 32 Assembly Rail[B]	PWR	17.7	32	0.553
			24	0.738
			16	1.106
PWR 18 Assembly Rail (South Texas)[C]	PWR	16.7	18	0.928
			12	1.392

Source: Total System Model Version 6.0 Transportation Design and Bases, 50040-DD-02-6.0-00, October 2007, Table 4

Notes:

[A]Assumed values from TN-68 TSC loaded from pool - BWR (CASK 66) and de-rated

[B]Assumed values from TN-32 TSC loaded from pool - PWR (CASK 76) and de-rated

[C]Assumed values from South Texas bare rail (CASK 60) and de-rated

The two different SSA methodologies considered were developed to demonstrate 1) how site-specific allocations could be developed to address different goals and 2) to evaluate the system level implications of different SSA approaches. The first aims for a steady-state acceptance rate and to completely remove all UNF from the reactor sites after a specified period of time after the last reactor on each site is shut down (SSA scenario). The second allows the annual allocation to fluctuate from year to year, aiming first to eliminate any further transfers of UNF from wet to dry storage, then to completely remove UNF from the reactor sites after a specified period of time after the last reactor on a site is shut down (DS and SSA scenario).

EVALUATION RESULTS

A key metric considered in this evaluation of UNF acceptance strategies is the time at which the last UNF is removed from each reactor site. As discussed above, the annual UNF allocation to a site does not necessarily equate to annual UNF acceptance from that site. For example, the thermal constraints on transportation casks, shown in Tables I and II, could limit the actual acceptance of UNF from the reactor sites to values lower than the annual allocation rates (i.e., 3000 MTHM, 4500 MTHM, or the values shown for the SSA strategies). In addition, the ability to load the needed number of transportation casks/overpacks to meet the annual allocation at the reactor sites could be limited by operational constraints at the reactor sites. This later constraint was not explicitly simulated in the TSL-CALVIN simulations, but was considered in the evaluation of the simulation results.

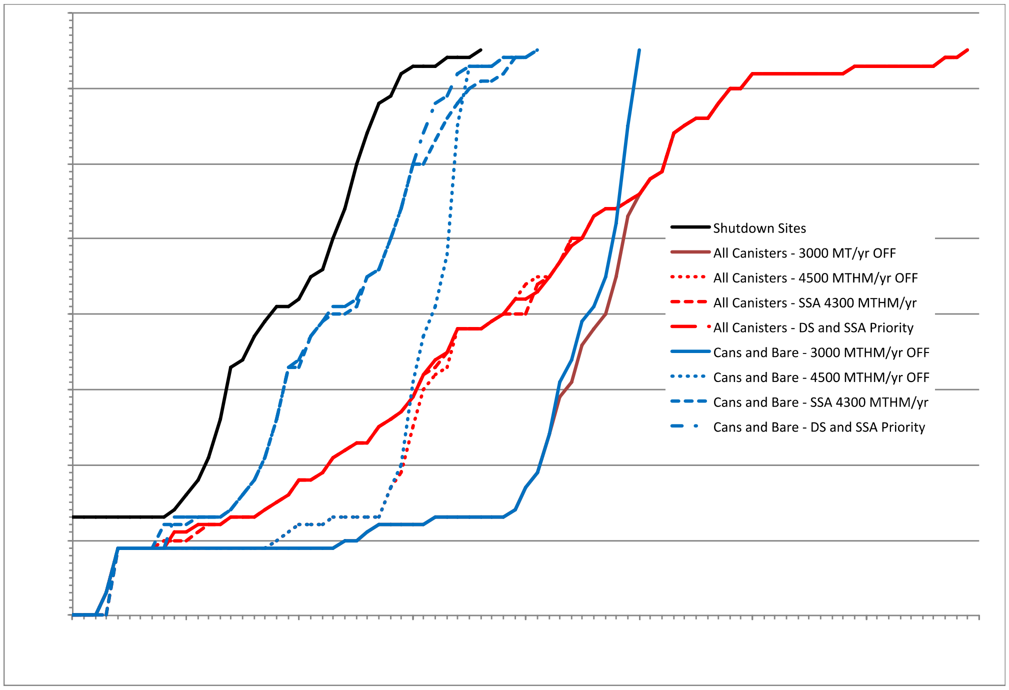
Figure 1 shows the TSL-CALVIN simulation results for the year in which UNF is completely removed from each reactor site for the different cases considered. Figure 1(a) shows the cumulative number of reactor sites that are completely cleared of UNF each year. Figure 1(b) shows the number of shutdown reactor sites with UNF still remaining on-site. The red curves show the UNF acceptance cases that ship all fuel from the reactor in large dry storage canisters. The blue curves show the UNF acceptance cases that transport fuel from the wet pools in re-useable transportation casks that can be de-rated to ship UNF with higher decay-heat.

The thermal constraints on dry storage canister transportation overpacks are the fundamental difference between the cases that transport all UNF in large canisters and the cases that transport UNF canisters from dry storage and bare fuel from the wet pools in re-useable transportation casks. For all allocation/ acceptance rates considered, in the canister only cases a significant amount of fuel residing in the wet pools does not meet the thermal limits on the dual purpose canister (DPC) transportation overpacks (see Table I) and cannot be shipped off-site. In such instances, the TSL-CALVIN simulator selects cooler canisterized fuel that is already in dry storage to be shipped off-site and, in order to maintain pool capacity, transfers UNF from wet storage into canisters that are stored onsite until they in turn are cool enough to be transported. A significant amount of time is required for those canisters to cool sufficiently and results in the tail shown on the red curves in Figure 1. Ultimately there is insufficient UNF available in DPCs that are cool enough to be transported off-site in DPCs to meet the annual allocation and UNF acceptance becomes driven by the rate that the loaded dry storage canisters cool sufficiently to be transported.

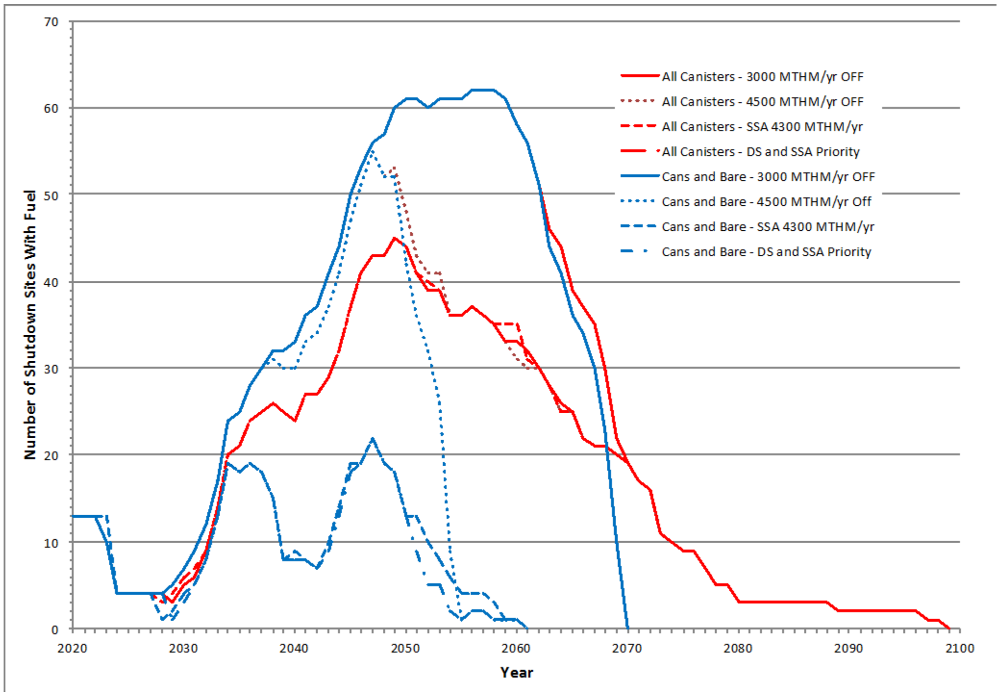
The bare fuel casks assumed in this analysis are capable of accommodating hotter UNF, primarily by reducing the number of assemblies loaded into the casks (referred to as de-rating, see Table II). Thus, all UNF from a wet pool that is allocated to be transported off-site that fuel can be removed. The desired allocation/acceptance rates rather than the thermal limits on dry storage canister overpacks drive the rate that UNF is removed from the reactor sites.

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

The maximum annual number of UNF handling operations is projected to be large (over 100 per year) for some of the simulation cases. The ability to perform a large number of cask/canister handling operations at reactor sites may be limited due to operational constraints, in particular when the reactor(s) are generating power. Nuclear utilities have a finite amount of time to off-load fuel between outages that depends on depends on plant configuration (number of cranes and pools) and competing activities. Times to load UNF into dry storage casks ranges from one to two weeks with much of this time not associated with the actual transfer of UNF. Additional time to load canisters and casks would be available after reactor shutdown. Further evaluation is needed to determine if the number of cask handling operations for the allocation/ acceptance scenarios considered are reasonable or to determine if there are other site-specific allocation/ acceptance scenarios that could be developed that take into account reactor site operational limitations.



a) Cumulative Number of Sites Cleared of UNF



b) Number of Shutdown Sites with UNF Remaining On-Site

Fig. 1. Shutdown Site Status for Different Allocation Strategies

Table III. Total number of site-years with UNF on reactor sites following reactor shutdown

Allocation/Acceptance	UNF Acceptance Approach	
	Canistered Fuel Transport	Bare and Canistered Fuel Transport
OFF (3000 MTHM/yr)	1900	1750
OFF (4500 MTHM/yr)	1500	875
Shutdown Priority - Steady SSA (~4500 MTHM/yr)	1350	410
Eliminate Additional Dry Storage, Shutdown Priority SSA (variable acceptance rate)	1350	380

It should be noted that the contents of transportation casks may be limited by external radiation dose levels of 10 CFR Part 71 rather than by thermal limits. The thermal limits for UNF transport casks are not set based on meeting dose rate criteria but are set so as to ensure safe margin to the temperature limits of contents and package components. The UNF heat loads in a UNF canister/cask may be correlated to higher dose rates, it is a complicated relationship 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.

Table IV provides estimates for approximate thermal limits at the cask transport radiological limit for three of the transportation overpacks in Table I. It can be seen that these approximate thermal limits are much more stringent than the thermal limits shown in Table I and could require longer at-reactor storage before fully-loaded large canisters could be transported off-site.

A sensitivity study was performed using TSL-CALVIN where the approximate thermal limits shown in Table IV were applied to show the potential impact of more stringent external radiation dose level limits on transportation casks. A 3000 MTHM/yr allocation/acceptance rate and the transportation of all UNF away from the reactor sites in large dry storage canisters were assumed.

Figure 2 shows the TSL-CALVIN simulation results for when UNF is completely removed from the reactor sites. Figure 2(a) shows the cumulative number of reactor sites that are completely cleared of UNF each year. Figure 2(b) shows the number of shutdown reactor sites with UNF still remaining on-site. The solid red curves show the UNF clearing results when the transportation overpack thermal limits provided in Table I are assumed. The dashed red curves show the UNF clearing results when the approximate transportation overpack thermal limits that correspond to radiation exposure limits provided in Table III are assumed.

Table IV. Dry storage canister transportation overpack thermal limits – radiological

Dry Storage Canister Transportation System	Capacity (Assemblies)	Thermal Limit[a] (kW)	Approximate Thermal Limit - Radiological (kW)
HI-STAR-100	24 P	20	13.7
	68 B	18.5	13.7
NAC UMS	24 P 56 B	20	16
Transnuclear MP197	24P	24	13.6
	61B	24	13.1

Source: Bechtel SAIC Company LLC, The Potential of Using Commercial Dual Purpose Canisters for Direct Disposal, TDR CRW-SE-000030 REV 00, November 2003 (Table 6)
[a]From Table I

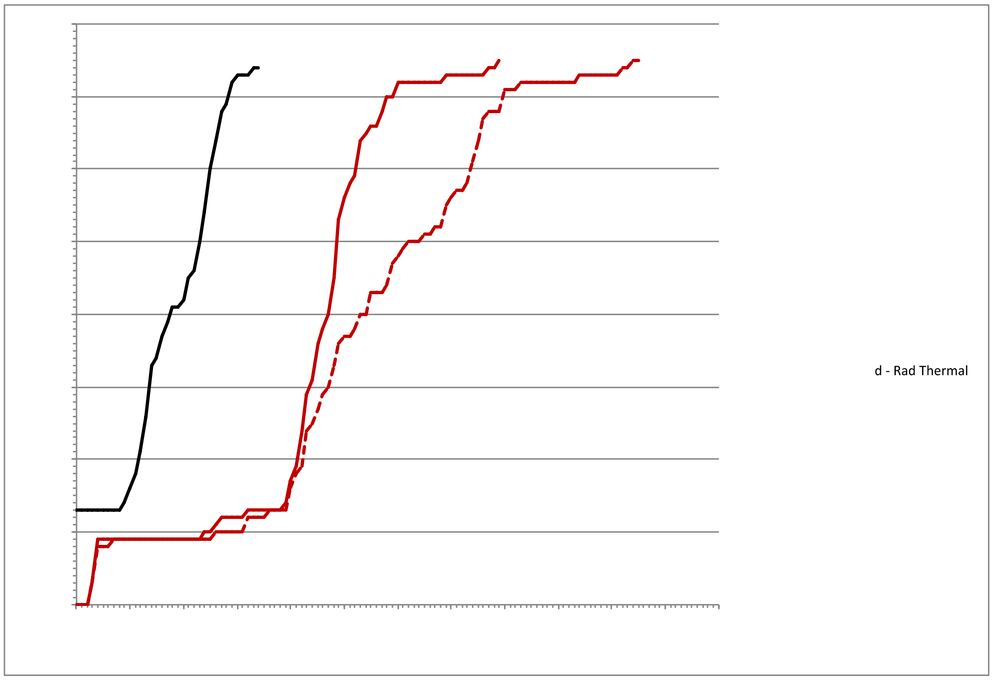
These results show that more stringent radiation exposure limits on dry storage transportation overpacks could further extend the time required to allow for radioactive decay before UNF in large canisters could be removed from reactor sites. In most cases reactor sites could not be completely cleared of UNF until later in this century and in some cases continued on-site storage into the next century may be required before UNF could be removed. Accelerating UNF acceptance and applying site-specific UNF would provide no significant benefit in regard to clearing UNF from the reactor sites under more stringent limitations on the dry storage canister transportation overpacks.

CONCLUSIONS

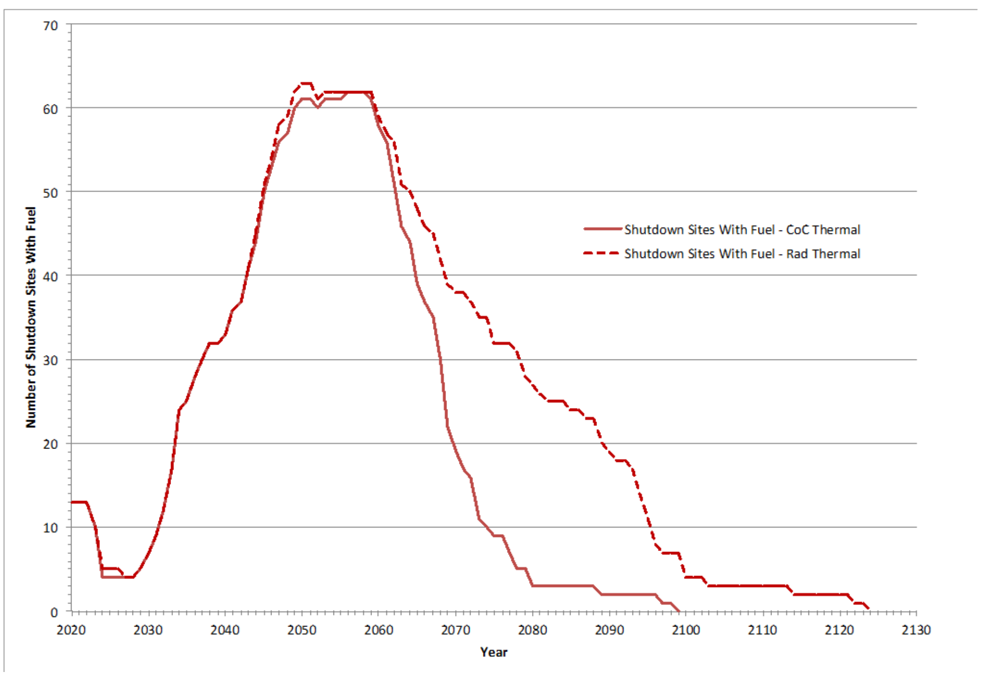
The following conclusions were drawn from this evaluation:

Thermal constraints on dry storage canister transportation overpacks have a significant effect on on-site UNF management and UNF acceptance. While an accelerated oldest-fuel first UNF acceptance strategy and site-specific allocation strategies can increase the rate that reactor sites are cleared of UNF, the UNF clearing of reactor sites for all four “all canister” shipment cases converge at about 2070. UNF acceptance is then driven by the rate that the loaded dry storage canisters cool sufficiently to be transported. Many of the hotter dry storage canisters are generated when the UNF pools are off-loaded to dry storage five years after reactor shutdown and these canisters have to sufficiently cool before being transported off-site, affecting when a site can be completely cleared of UNF.

- The total amount of UNF loaded into on-site dry storage and the maximum inventory of UNF in at-reactor dry storage is larger for the “all canister” shipment cases compared to the cases where bare fuel is shipped from the UNF pools. This is due to the thermal constraints on the transportation overpacks.



a) Cumulative Number of Sites Cleared of UNF



b) Number of Shutdown Sites with UNF Remaining On-Site

Fig. 2. Potential Impacts of Transportation Cask Limits on UNF Clearing of Reactor Sites – 3000 MTHM/yr OFF Allocation/Acceptance, All Canisters

- Transporting UNF from the pools in re-useable transportation casks that can accommodate hotter UNF assemblies could allow for accelerated clearing of UNF from the reactor sites. The actual acceptance rate is not driven by thermal constraints on the transportation casks/overpacks and can match the desired allocation/acceptance rate, assuming that at-reactor operational limitations are not constraining.
- Site-specific UNF allocation/acceptance strategies that aim to clear all of the reactor sites of UNF within five years following the last reactor shutdown at each site could not be achieved if all UNF from the reactor sites is transported using fully-loaded dry storage canisters. Such an allocation/acceptance strategy could be achieved if UNF from the pools is transported in re-useable transportation casks that can accommodate hotter UNF assemblies. However, the maximum number of casks/overpacks accepted in a given year could be large.
- Site-specific UNF allocation/acceptance strategies that aim to clear reactor sites of UNF within five years following the last reactor shutdown at each site combined with accepting both canistered and bare fuel may provide the ability to significantly reduce the at-reactor UNF management burden as measured in fuel-on-site years.

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