Waste Management System Architecture Evaluations

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INTRODUCTION

The Nuclear Fuel Storage and Transportation Planning Project (NFST), under the U.S. Department of Energy, Office of Nuclear Energy, Office of Fuel Cycle Technologies, is developing tools and techniques, gathering data and information, and conducting analyses to inform future decisions regarding the waste management system. Used Nuclear Fuel (UNF) 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. Flexibility, adaptability, phasing, and step-wise learning are key considerations for evaluating the system.

USED FUEL MANAGEMENT SYSTEM ARCHITECTURE EVALUATION

The Used Fuel Management System Architecture Evaluation effort provides information regarding the various alternatives for managing 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 them with respect to cost and flexibility
- Consider a broad range of factors including repository emplacement capability, thermal constraints, re-packaging 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 objectives of the initial effort [1], were two-fold: 1) develop methodologies, approaches, and tools (capability development), and 2) use them to evaluate select UNF disposition scenarios (capability demonstration). 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] built on the previous work and continued the development of methodologies, approaches and tools, and broadened the suite of UNF disposition scenarios that were evaluated based on the insights gained and recommendations made in the 2012 effort.

Activities continued in 2014 and the results and insights gained are summarized 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 UNF 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") [3]. However, assumptions, inputs, and potential interface constraints with respect to the pilot 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 UNF in canisters to be an acceptable waste form, absent a mutually agreed to contract modification. To ensure the ability to transfer UNF to the government under the Standard Contract, the individual spent fuel assemblies must be retrievable for packaging into a DOE-supplied transportation cask.

SYSTEM ANALYSIS OF ALTERATIVE UNF ACCEPTANCE STRATEGIES

A key aspect of the analysis of system scenarios is the assumption about the priority for allocation of available UNF acceptance capacity among reactors. The previous analyses [1,2] indicated that acceptance priority assumptions have a significant impact on the UNF management system and that modifications to the 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 UNF 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 UNF transport 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 UNF heat loads in a UNF canister/cask may be correlated to higher dose rates, however 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]

In the present study integrated waste management system analyses were completed to further explore alternative acceptance priority strategies that had previously been studied [2] and for additional alternative acceptance priority strategies. These analyses considered the following:

- UNF packaging/re-packaging into disposal canisters performed at a geologic repository.
- Two scenarios for accepting UNF from the reactor sites: transport of fuel packaged into existing size dual-purpose canisters (DPCs) only or transport of bare fuel in re-useable transportation casks as well as canisterized fuel.
- A Pilot ISF that begins operation in 2021, consistent with the Administration's Strategy [3]. For this analysis, the Pilot ISF is assumed to serve the removal of all UNF from nine shutdown sites (Maine Yankee, Yankee Rowe, Connecticut Yankee, Humboldt Bay, Big Rock Point, Rancho Seco, Trojan, La Crosse, and Zion) in 4 years.
- A larger ISF that begins operation in 2025, consistent with the Administration's Strategy. As explained below, a range of acceptance priority strategies is considered for acceptance of UNF from the operating fleet of commercial reactors and transported to the larger ISF.
- A geologic repository that begins operation in 2048, consistent with the Administration's Strategy. A single geologic repository acceptance and emplacement rate of 3,000 MTHM per year was assumed.
- When the reactors shut down it is assumed that:
    - For cases when 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.
    - For cases when a combination of bare fuel and canisterized fuel is used to transport UNF from the reactor sites, none of the UNF remaining in the pools is transferred to dry storage after reactor shutdown. UNF in the wet pools following shutdown remains there until transported directly off-site.

UNF Acceptance Strategies Considered

The cases evaluated using the Transportation Storage Logistics (TSL) simulator consider sixteen different UNF allocation scenarios representing combinations of three annual larger ISF acceptance rates (3,000 MTHM, 4,500 MTHM, and a variable rate) and five acceptance priority assumptions (OFF and four different approaches for site-specific allocation). In this context annual allocation determines how much UNF is allocated to be shipped from each site in a given year. As in previous analyses [1, 2], 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-over-5-years-old-first (YFF-5) principle. The amount of fuel shipped from the reactors, termed "acceptance", may be less than the amount allocated, primarily due to the thermal constraints discussed above.

The four different site-specific allocation (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 following abbreviations are used in the shorthand names for the allocation approaches that are underlined below:

SSA — **S**ite **S**pecific **A**llocation

DS — Eliminate additional **D**ry **S**torage at operating reactors

SD — Empty **S**hut**D**own reactor sites

P — Only take fuel from reactor sites after the last reactor at the site has shut down (**P**ost-shutdown)

<u>DS-SD Priority</u>: Site Specific Allocation (SSA) approach with goals to: 1) give priority to current shutdown sites, 2) eliminate additional transfer of UNF from the pools to on-

site dry storage once acceptance begins (DS), and 3) clear remaining shutdown sites (SD) in order of license expiration date as soon as possible while maintaining the overall allocation/acceptance rate at 3,000 or 4,500 MTHM/yr.

<u>P-SD Priority</u>: SSA approach with goals to 1) give priority to current shutdown sites, 2) only allocate/accept from other sites after (P) shutdown (SD) while maintaining the overall allocation/acceptance rate at 3,000 MTHM/yr or 4,500 MTHM/yr.

<u>SD-5 Priority 4500 MTHM/yr</u>: SSA approach with goals to: 1) give priority to current shutdown sites, 2) clear remaining sites of UNF 5 years after last reactor at a site ceases operation; and 3) maintain a steady acceptance rate near 4,500 MTHM/yr

<u>DS-SD Priority, Variable</u>: SSA approach with goals to: 1) give priority to current shutdown sites, 2) eliminate additional transfer of UNF from the pools to on-site dry storage once acceptance begins, and 3) clear remaining sites 5 years after last reactor at a site ceases operation over a ten year period (from 5 years before to 5 years after the last reactor at a site ceases operation).

AT-REACTOR UNF ACCEPANCE STRATEGY LOGISTIC SIMULATION RESULTS

A key metric considered 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 the calculated annual UNF acceptance from that site. As also discussed above, the thermal constraints on transportation casks could limit the actual acceptance of UNF from the reactor sites to values lower than the annual allocation rates assumed for each case. 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. The later constraint is not explicitly simulated in TSL, but is considered in the evaluation of the simulation results.

Figure 1 shows the TSL simulation results for the year in which UNF is completely removed from each reactor site for the different alternative acceptance strategies. The red curves show the acceptance strategies that ship all fuel from the reactor sites in large DPCs. The blue curves show the acceptance strategies that transport fuel from the pools in re-useable transportation casks that can be de-rated to ship UNF with higher decay-heat thermal output.

The area under each curve in Figure 1 represents the total years with UNF on each reactor site after the las reactor on site has shut down integrated over all sites (site-years). 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), and the community impact (since a site cannot be repurposed until decommissioning and UNF removal is complete). The total number of post-shutdown years with UNF on site is summed over all sites (fuel-on-site years) and is shown in Figure 2.

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 pools in re-useable transportation casks. For all allocation/acceptance cases considered that involve the acceptance of only canisters, a point is reached at several reactors at which so much older, cooler fuel has been removed from the pools that a DPC that is fully-loaded using the remaining hotter fuel will not meet the thermal limits on the DPC transportation overpacks and cannot be shipped directly from the pools off-site. In such instances, TSL selects cooler canisterized fuel that is already in dry storage to be

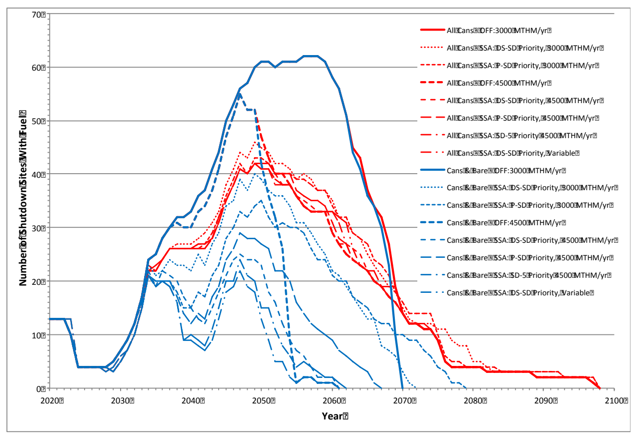

Fig. 1. Shutdown Site Status for Different Allocation Strategies.

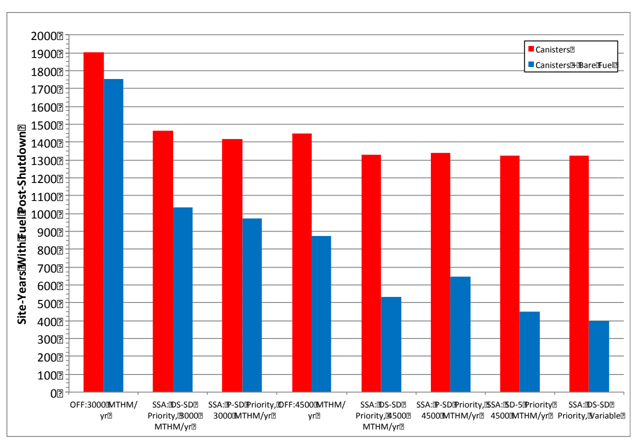

Fig. 2. Site-Years with UNF On Reactor Sites Post Shutdown.

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, sometimes on the order of 10 or more years, is required for those canisters to cool sufficiently. Ultimately there is insufficient UNF available in DPCs that are cool enough to be transported off-site to meet the annual allocation and UNF acceptance becomes driven by the rate that the loaded dry storage canisters cool sufficiently to be transported. This results in the tail shown on the red curves in Figure 1, which is similar for each alternative allocation/acceptance approach considered.

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 either by loading large casks to less than their full capacity (referred to as short-loading) or by using purpose-designed transportation casks with smaller capacity. Thus, when UNF from a pool 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.

It should be noted that short-loading could be used to load large DPCs with UNF from the pools or smaller canisters with higher thermal constraints could be selected such that the thermal limits on the transportation overpacks are met. While these alternative allocation/ acceptance approaches were not evaluated, the results would be similar to those shown for the approaches that accept bare fuel with respect to the rate that sites could be cleared of UNF. However, an increased number of canisters would have to be loaded and shipped as compared to the results that are presented later. This could have an impact on the configuration, inventory of canisters stored, and operation of the ISF. Further analysis is recommended.

The total number of large UNF canister/cask handling operations that occur each year was calculated at every reactor site from the simulation results by summing the following:

- Transfers from pool storage to dry storage
- Transfers from pool storage for direct transport offsite
- Transfers from dry storage for direct transport offsite

These calculations were used to generate histograms of the frequency of large UNF canister/cask handling operations at individual reactor sites annually for each UNF acceptance strategy for sites with operating reactors and sites where all reactors are shut down. An example is shown in Figure 3. The TSL simulator does not consider any constraints when simulating UNF handling operations. As an example, in the all canister allocation/ acceptance cases TSL models the transfer of all UNF in the fuel pools to dry storage as occurring over a period of one year beginning 5 years after plant shutdown. In reality, this operation would likely be done over a longer time period.

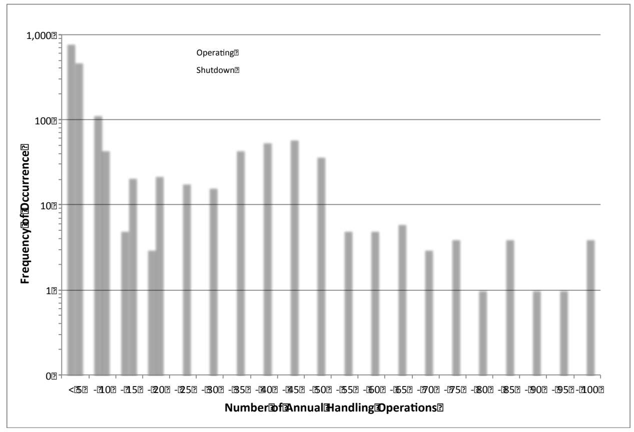

Fig. 3. Total Annual Handling Operations

There are only specific, limited time windows when fuel, canisters, and casks could be handled at reactor sites and there is a specific amount of time associated with each handling operation. There are site-specific factors that affect the windows when fuel handling operations could occur, such as the number of reactors on site and the number and configuration of fuel and cask handling cranes. In addition, activities that support operation of nuclear power plants can conflict with being able to handle fuel, canisters, and casks.

Fuel handling windows were estimated for operating nuclear sites for different reactor configurations and operating fuel cycle strategies (18 month versus 24 month). The windows where fuel, canisters, and casks can be moved are constrained at sites with operating nuclear power plants. The constraints are not as stringent once a plant is shut down and enters decommissioning. Essentially all available time can be used to handle fuel, canisters, and casks.

Recent experience in loading dry storage systems indicates that approximately one cask can be loaded per week with the industry loading at most between 10 and 15 DPCs into dry storage during a campaign. While this experience is with loading dry storage systems, the loading of large bare fuel casks that would be transported by rail would take a similar amount of time. There is no experience in removing canisters from dry storage for off-site transport, but it is expected that this process would be significantly less time consuming and less time-constrained because it does not require use of the reactor pool for which there are other competing uses.

Given this, the calculated large UNF cask/canister handling operations were used to identify those allocation/acceptance approaches that would likely be challenging or impossible to execute at the reactor sites.

It was assumed in this analysis that 20 annual handling operations could be conducted as sites while there are reactors operating and 50 annual operations could be conducted at sites where all reactors at the site have shutdown for comparison to the histograms developed for each acceptance strategy. A high frequency of annual operations that exceed these limits would be indicative of challenging allocation/ acceptance approaches. For lower frequencies (e.g., single digits), the acceptance/allocation approach could be improved to 'spread out' the number of handling operations needed.

None of the allocation/acceptance strategies appear to be challenging with respect to handling operations after reactor shutdown. However, during reactor operations it appears that two of the allocation/acceptance approaches would be challenging to implement. The cases identified below have a large frequency of fuel handling operations that exceed the limit of 20 annual operations discussed above:

- SD-5 Priority 4500 MTHM/yr
- DS-SD Priority, Variable

Further evaluations of at-reactor logistics constraints are needed using waste management system analysis tools that can explicitly model those constraints (i.e., windows where casks/canisters can be loaded).

The following conclusions can be drawn from the at-reactor logistic simulation results:

- Thermal constraints on dry storage canister transportation overpacks significantly affect 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 "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. Either de-rating canister loading or using smaller canisters that can accommodate hotter UNF assemblies could potentially alleviate this. Additional evaluations are needed to understand the impacts on the entire waste management system.
- The total amount of UNF loaded into on-site 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 and the assumption that canisters were not short-loaded, leading to the following:
    1. During some years there is not enough sufficiently cooled UNF in the pools at some reactor sites to allow a large dry storage canister to be fully loaded and still fall below the thermal limit for transportation so it could be directly shipped offsite. In such cases, sufficiently cooled canisters of UNF are shipped from dry storage instead, and an equivalent amount of UNF is transferred from the pools to dry storage in fully loaded canisters in order to maintain pool capacity, essentially replacing the UNF that has been transported from dry storage.
    2. During some years there is not sufficiently cooled UNF in either the pools or in dry storage at some reactor sites to be transported off-site in fully-loaded DPCs. Again, UNF is transferred from the pools to dry storage to maintain pool capacity, further adding to the dry storage inventory.
    3. There is still UNF in the pools five years after the reactors have shutdown and all of this fuel is transferred to dry storage, rather than remaining in the UNF pools until being shipped off-site as would be the case in the bare fuel acceptance scenarios.
- Transporting UNF from the pools in re-useable transportation casks that can accommodate hotter UNF assemblies could allow for accelerated UNF clearing of 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 UNF from all of the reactor sites within a short period of time (e.g. five years as evaluated herein) following the last reactor shut down at each site could not be achieved if all UNF from the reactor sites is transported using fully-loaded large dry storage canisters. Such an allocation/acceptance strategy could be achieved if UNF from the pools is either loaded into smaller canisters or short-loaded large canisters or 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. Further evaluation of scenarios where smaller canisters or short-loaded large canisters are loaded is needed.
- Site-specific UNF allocation/acceptance strategies that aim to clear UNF from all of the reactor sites within a short period of time (e.g. five years as evaluated herein) 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.

- The number of annual UNF handling operations at each reactor site increases as the acceptance rate increases (i.e., from 3,000 MTHM/yr to 4,500 MTHM/yr) for the oldest-fuel-first cases and increases further when site-specific allocation strategies are considered. The results indicate that improved site-specific allocation strategies could be developed to reduce the number of fuel handling operations required each year by spreading the total number of handling operations needed over a longer period of time while aiming to clear UNF from the reactor sites as soon as possible. The results also indicate that very aggressive allocation/acceptance scenarios that increase the amount of UNF that would need to be handled while reactors at a site are operating may not be achievable. Additional evaluations are needed that explicitly model the windows at the reactor sites when fuel could be handled and the unit processing times for the handling operations.

INTERIM STORAGE FACILITY UNF MANAGEMENT LOGISTIC SIMULATION RESULTS

The effects of the different allocation/acceptance strategies on an interim storage facility (ISF) were also evaluated using TSL. It was assumed that a repository would begin operation in 2048, consistent with the goal in the Administration's Strategy [3], and that the repository would accept UNF at a rate of 3,000 MTHM/yr. It was also assumed that UNF is shipped from the reactor sites to the repository after it begins operation in 2048 until no UNF is available from the reactor sites, at which time UNF is shipped from the ISF to the repository. Dry storage canisters received at the ISF were assumed to be stored in a dry configuration and bare fuel received at the ISF was assumed to be stored in pools. These assumptions are consistent with those made in previous analyses [1].

Figures 4 and 5 show the maximum ISF capacity and the number of ISF receipt bays that would be required for those allocation/acceptance scenarios where only DPCs are shipped to the ISF. Similar figures were generated for the cases when both DPCs and re-useable bare fuel transportation casks were shipped to the ISF. These results demonstrated that:

- With a fixed repository acceptance rate, higher acceptance rates from the reactors result in additional UNF receipt bays and larger UNF inventories at the ISF.
- The total ISF inventory, in terms of MTHM stored, was found to be larger when bare fuel is accepted from the pools. This is because a larger amount of

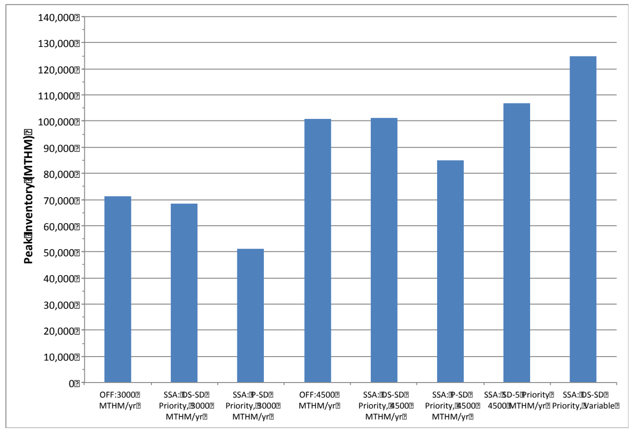

Fig. 4. Maximum ISF Inventory

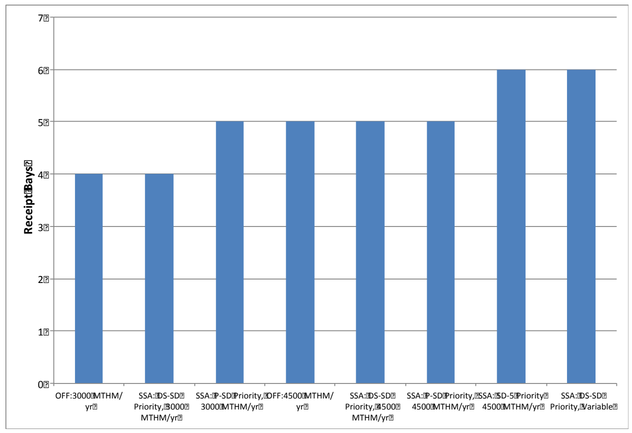

Fig. 5. Number of ISF Receipt Bays

UNF arrives at the ISF before the repository begins operation in 2048. When all UNF is shipped in canisters the shipment of some UNF is deferred past 2048 due to thermal constraints and is shipped directly to the repository when sufficiently cooled.

- A large capacity bare fuel storage capability would be needed at the ISF if bare fuel were accepted from the pools at the reactors and stored in a bare configuration. For example, between approximately 30 and 100 basins (8 basins per pool) would be needed to accommodate the maximum inventory (from about 25,000 MTHM to about 93,000 MTHM) if wet pools were chosen as the ISF storage technology, depending on the acceptance rate and UNF allocation/acceptance approach.

SUMMARY INSIGHTS FROM THE UNF ACCEPTANCE STRATEGY ANAYSES

The evaluation of alternative UNF acceptance strategies resulted in several high level insights, identified additional analyses that should be performed, and identified necessary waste management system model enhancements. At a summary level, these are:

- Site-specific allocation/acceptance strategies could lead to significant benefits with respect to at-reactor management logistics and costs. Such strategies may allow for more efficient clearing of UNF from the reactor sites than would be attainable under an oldest-fuel-first allocation approach.
- Accelerating acceptance can also have benefits with respect to at-reactor management logistics and costs. Accelerating acceptance in combination with site-specific allocation/ acceptance could potentially be the most efficient approach for clearing UNF from the reactor sites. However, very aggressive allocation/acceptance strategies and rates would be challenging, if not impossible, to achieve considering the constraints associated with moving UNF at the reactor sites.
- Additional evaluation of UNF acceptance strategies is necessary to better understand their feasibility with respect to reactor site operations. Waste management system analysis tools need to be improved to better represent windows when UNF can be moved at the reactor sites.
- The strategy for accepting UNF from the reactor fleets will have an impact on the design, configuration, and operation of an ISF. The form of the UNF that would be accepted (canisters, bare fuel assemblies) and the rate the UNF is accepted will effect the number of canister/cask processing bays needed and the overall amount of UNF that would be stored at the ISF.
- The selection of an acceptance rate from the reactor fleet (i.e., 3,000 MTHM/yr) may influence the preferred strategy regarding the form of the UNF that would be accepted. From an overall system perspective, there may be advantages to accepting all UNF in dual-purpose canisters for acceptance rates on the order of 3,000 MTHM/yr. However, it may be beneficial to accept both bare fuel in re-useable transportation casks along with dual-purpose canisters if the acceptance rate is increased.
- Improved confidence in at-reactor UNF management costs along with better understanding of ISF design concepts would allow for better understanding of system impacts of different UNF allocation/acceptance strategies. The NFST is currently developing modular ISF design concepts for dry storage and the results from that effort can be implemented into future waste management system analyses. However, the development of ISF design concepts for bare fuel storage is not as mature.
- Constraints on UNF transportation casks/overpacks, such as thermal or radiation exposure limits, can have a significant impact on the ability to clear UNF from reactor sites for the different UNF allocation/acceptance strategies. These constraints are well understood for DPC systems. Designs designs certified by the U.S. NRC to meet the 10 CFR 71 requirements for re-useable transportation are limited and at present it was necessary to assume those constraints for large re-useable bare fuel casks transported via rail in the analyses completed to date. Bare fuel cask design concept development work underway should provide a better understanding of those constraints.

The approach for loading DPCs in current system analysis modeling tools do not reflect how they are typically loaded or would be loaded at the reactor sites while taking thermal limits into account. The current waste management system analysis tools also do not estimate external radiation exposure on loaded transportation casks/overpacks for comparison with 10 CFR 71 limits. Efforts are being initiated to define these approaches and implement them into waste management system analysis tools.

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