Used Fuel Management System Interface Analyses – 13578

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ABSTRACT

Preliminary system-level analyses of the interfaces between at-reactor used fuel management, consolidated storage facilities, and disposal facilities, along with the development of supporting logistics simulation tools, have been initiated to provide the U.S. Department of Energy (DOE) and other stakeholders with information regarding the various alternatives for managing used nuclear fuel (UNF) generated by the current fleet of light water reactors operating in the United States. An important UNF management system interface consideration is the need for ultimate disposal of UNF assemblies contained in waste packages that are sized to be compatible with different geologic media. Thermal analyses indicate that waste package sizes for the geologic media under consideration by the Used Fuel Disposition Campaign may be significantly smaller than the canisters being used for on-site dry storage by the nuclear utilities. Therefore, at some point along the UNF disposition pathway, there could be a need to repackage fuel assemblies already loaded and being loaded into the dry storage canisters currently in use. The implications of where and when the packaging or repackaging of commercial UNF will occur are key questions being addressed in this evaluation. The analysis demonstrated that thermal considerations will have a major impact on the operation of the system and that acceptance priority, rates, and facility start dates have significant system implications.

INTRODUCTION

In the 1990s the U.S. Department of Energy (DOE) completed a number of system analyses investigating consolidated interim storage as a part of the waste management solution.[1,2] These analyses do not reflect the present situation regarding at-reactor used nuclear fuel (UNF) management, alternatives for away-from-reactor management of UNF, and alternatives for the ultimate disposal of UNF. The Blue Ribbon Commission for America's Nuclear Future [3] and the Nuclear Waste Technical Review Board [4] have also pointed out the need for such analyses.

The Used Fuel Management System Architecture Evaluation effort provides the DOE and others with information regarding the various alternatives for managing UNF generated by the current fleet of light water reactors operating in the United States. The objectives are as follows:

- 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, and
- Consider a broad range of factors including repository emplacement capability, thermal constraints, repackaging needs, storage and transportation alternatives, and impacts on utility operations.

In Fiscal Year 2012 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. The objectives of the initial effort were twofold: (1) develop methodologies, approaches, and tools (capability development); and (2) evaluate select UNF disposition scenarios (capability demonstration). The scenarios chosen for evaluation and the assumptions, inputs, and boundary conditions selected lead to a set of analyses to gain insight regarding integrated system dynamics and an understanding of trends. This initial set of analyses also points to where additional system architecture analyses should focus.[5]

An important waste management system interface consideration is the need for ultimate disposal of UNF fuel assemblies contained in waste packages sized to be compatible with the geologic medium of the final repository. Thermal analyses completed by the Used Fuel Disposition Campaign (UFDC) indicate that waste package sizes for the geologic media under consideration by the UFDC are significantly smaller than the canisters being used for on-site dry storage by the nuclear utilities.[6,7] Therefore, at some point along the UNF disposition pathway there may be a need to re-package fuel assemblies already loaded into the types of dry storage canisters currently in use unless the feasibility of direct disposal of these large canisters can be demonstrated. Note that evaluating the feasibility of the direct disposal of dual purpose canisters is underway.[8] The implications of where and when the packaging or re-packaging of commercial UNF will occur are key questions being addressed in this evaluation.

DESCRIPTION

A range of disposition pathways that consider a broader set of alternatives to investigate how they might contribute to the overall flexibility of the UNF management system were considered. These alternatives include the storage of commercial UNF at an off-site Consolidated Storage Facility (CSF), canisterization of bare fuel at reactors, packaging/re-packaging of UNF at either the CSF or a repository, wet or dry packaging/re-packaging, multiple CSFs with different capacities, different repository environments having different waste package size limitations, and different throughputs at the CSF and at the repository. In order to keep the initial evaluation at a manageable size, disposition pathways that considered multiple CSFs and dry repackaging facilities were not considered in the first set of evaluations.

Logistics Framework

A broad logistic framework that identifies the potential pathways for fuel assemblies stored at-reactor, either wet or dry, through CSF, followed by UNF packaging/repackaging into disposal canisters for ultimate disposition in a geologic repository was first developed.

This framework development began with the initial state of conditions as they currently exist and are expected to continue:

- Fuel assemblies are stored as bare fuel in the used fuel pools at each reactor site.
- Fuel assemblies are transferred from the used fuel pools to dry storage systems at each reactor site to maintain full-core off-load capacity within the wet pools. The dry storage systems utilized are those currently being loaded [termed “existing-size” casks/canisters, or Existing-Size Canisters (ESCs)].

- All remaining fuel assemblies are transferred from the wet pools to ESC systems at each reactor site 5 years after the reactor is shut down.

Three different alternatives for future at-reactor management of UNF were also considered in developing the broad UNF disposition framework;

- Transfer of bare fuel in re-useable transportation casks directly to the CSF when the reactor is shut down and a CSF is available. This alternative requires bare fuel handling capability at the CSF and maintaining the bare fuel in the pools at the reactor sites until it is all shipped.

- Transition from ESC systems to loading Waste Package-Size Canisters (WPSCs) at the reactor sites. Such canisters would not have to be reopened and the individual fuel assemblies repackaged prior to emplacement in a repository. The maximum fuel assembly capacity of the waste package compatible-size canisters depends on the media and design concept of the repository assumed (see Table I).

- Accelerate the transfer of fuel assemblies from the used fuel pool to at-reactor dry storage. In this option, all fuel assemblies residing in the wet pools for a period of time greater than 5 years post reactor discharge would be transferred to dry storage as fast as possible.

TABLE I. Waste Package Capacity for Generic Media

Media/Design Concept	**Waste Package Size**	**Discussion**
Deep borehole	1 PWR/2 BWR	Limited by diameter of deep borehole (could be 2 PWR/4 BWR if fuel is consolidated)
Clay/shale: enclosed	4 PWR/9 BWR	100°C Limit, 50-year-cooled fuel
Crystalline: enclosed	4 PWR/9 BWR	100°C Limit, 100-year-cooled fuel
Salt: enclosed	12 PWR/24 BWR	200°C Limit, 50-year-cooled fuel
Clay/shale: open	21 PWR/44 BWR	100°C Limit, 50-year-cooled fuel

A range of different options was considered for the CSF facilities in developing the broad logistics framework:

- Storage of existing-size dry storage canisters

- Storage of waste package compatible-size dry storage canisters

- Storage of bare fuel

- Re-packaging capability for ESCs (wet or dry) either upon receipt at the CSF or prior to transport to a repository

- Packaging capability for bare fuel (wet or dry) upon receipt at the CSF

- Bare fuel packaging and/or canister re-packaging either upon fuel assembly receipt at CSF or prior to transport to a repository

Three options were considered for the repository:

- Direct disposal of waste package compatible-size canisters
- Repackaging of existing-size canisters (wet or dry)
- Packaging of bare fuel (wet or dry)

A high-level diagram of the alternative UNF disposition pathways is shown in Figure 1 and involves UNF storage at a (CSF) and UNF packaging/repackaging prior to ultimate disposal.

While the reactors will continue to transfer UNF to dry storage, there will always be UNF in the used fuel pools, at least until a reactor is shut down and decommissioned. Another important aspect is how the UNF residing in the used fuel pools is managed when fuel acceptance from the reactor sites begins. UNF residing in the pools could either be transported off-site in re-useable transportation casks, or placed in dual-purpose canisters suitable for both storage and transportation, or placed in a standard canister once one is designed and licensed. The choice impacts the design of both a CSF (canistered fuel storage only or canistered and bare fuel storage) and the quantity of UNF that would ultimately have to be re-packaged from existing-size canisters into waste package compatible-size canisters.

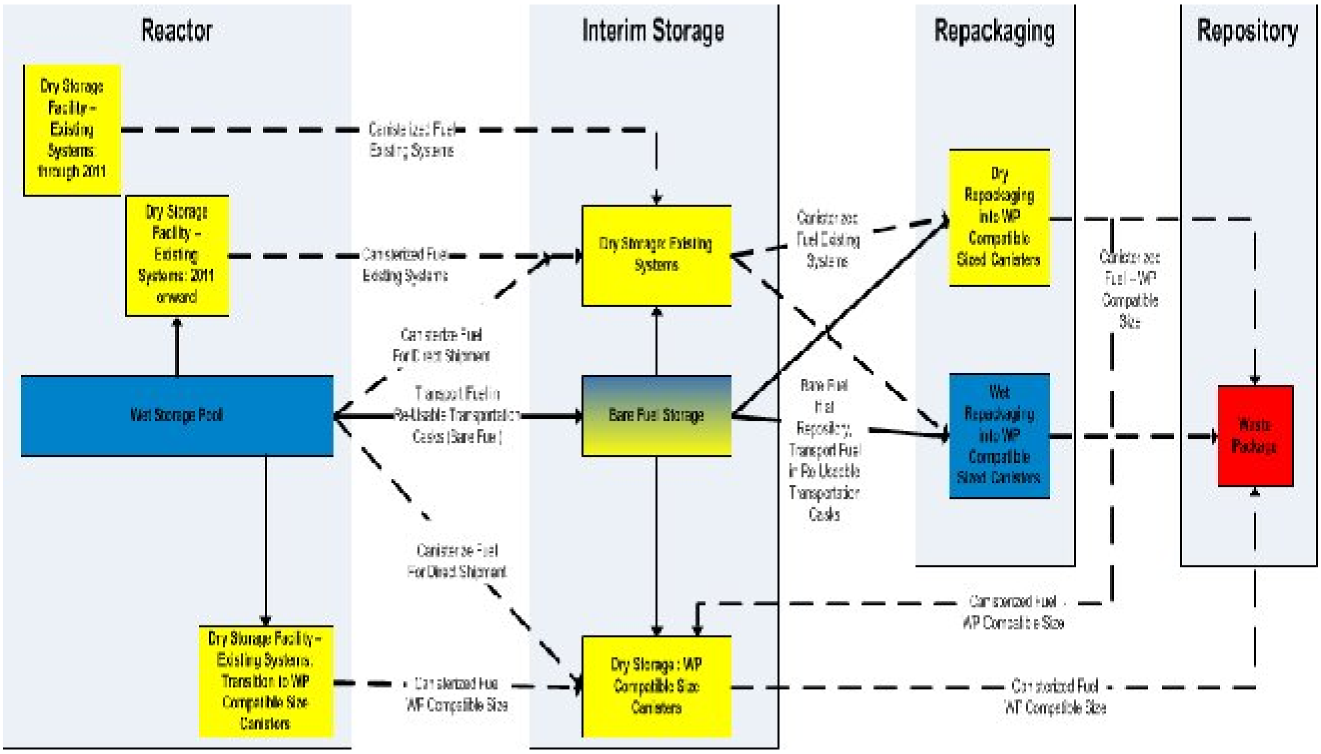


Fig. 1. Alternative used nuclear fuel disposition pathways.

These considerations resulted in the identification of nine potential disposition pathways that consider how UNF would be transported from the used fuel pools at the reactors, where UNF packaging/re-packaging would be performed (repository or CSF), and when UNF packaging/re-packaging would be performed (at

CSF receipt or prior to shipment from the CSF to a repository). These nine disposition pathways were evaluated considering complexity and flexibility, resulting in a down-select of the disposition pathways that were considered in the initial system architecture evaluation to four, representing the possible combinations of two features: what would be accepted from reactors by the waste management system (all UNF packaged into existing size canisters, or bare fuel as well as canisterized fuel), and where/when the UNF would be packaged/re-packaged for disposal (at a CSF when the fuel is about to be sent to the repository, or at the repository when fuel is received there). The packaging/re-packaging of bare fuel/canisters into disposal-size canisters at reactors or into either existing-size or disposal-size canisters at CSF receipt were not evaluated in this phase of the analysis.

The cases considered are summarized in Table II.

TABLE II. Simulation Case Matrix for Initial UNF System Architecture Evaluation

	Case 1	**Case 2**	**Case 3**	**Case 4**
Transport from reactors	Existing-size canisters	Existing-size canisters/ bare fuel	Existing-size canisters	Existing-size canisters/ bare fuel
Storage mode at CSF	Existing-size canisters	Existing-size canisters/ bare fuel	Existing-size canisters	Existing-size canisters/ bare fuel
Package/ Re-package at ==>	Repository	Repository	CSF	CSF
Transport from CSF to Repository	Existing-size canisters	Existing-size canisters/ bare fuel	Waste package-size canisters	Waste package-size canisters

Assumption and Input/Boundary Conditions

A range of assumptions and input/boundary conditions were used to evaluate the disposition pathways shown in Table I to give insights about those that have implications that might warrant consideration of alternatives.

- Disposition of used LWR fuel in a once-through fuel cycle
- The reactor fleet is limited to the current 104 operating reactors
- Reactors will receive life extensions to operate for 60 years
- Projected fuel inventory at reactor; wet and dry
- Oldest Fuel First (OFF) allocation priority (determines which reactor sites ship and how much is shipped from each site in a given year)
- Youngest Fuel First shipment from reactors (determines the fuel within the annual allocation that is shipped from each site)
- First-In-First-Out shipment from storage facility
- Reactors off-load pools to dry storage 5 years after shutdown
- Single CSF and geologic repository
- CSF and repository are not co-located
- Wet storage for bare fuel at the CSF
- Wet fuel assembly packaging and re-packaging

- Thermal constraints on geologic media were not considered, beyond the size of the waste packages discussed below
- CSF available: 2020, 2035
- Geologic repository available: 2040, 2055
- Acceptance rates: 1500, 3000, 6000 MTHM per year
- Waste package sizes: 4, 12, 21 PWR; 9, 24, 44 BWR

The assumptions and input/boundary conditions were selected to "constrain" the problem, but do provide a broad enough range to show trends and gain insight (i.e., the range in acceptance ranges and start dates). The choice of these assumptions and input/boundary conditions was not meant to imply that the system would actually be operated as assumed. As an example, the allocation priority and shipment schemes selected are those that have been looked at in prior UNF system analyses and provide a logical starting point. Rather, the initial set of assumptions, input/boundary conditions, and subsequent analyses allow for gaining insight regarding integrated system dynamics and understanding of trends, pointing to where the next set of system architecture analyses should focus.

The combination of disposition pathways and input parameters results in 36 individual scenarios that were evaluated.

Simulation Capability Development

The Transportation-Storage Logistics (TSL) simulator was developed in parallel with development of the logistics framework. This effort involved the modification and enhancement of legacy UNF logistics simulators previously developed by the DOE to result in a logistic simulator capable of modeling the range of disposition pathways and input parameters discussed above. [9,10] The TSL was used to simulate each of the 36 individual scenarios, using the assumptions and input/boundary conditions above, to provide information on a range of logistic parameters including quantities of UNF in at-reactor dry storage, shipping rates for the different types of dry storage canisters and bare-fuel assemblies from the reactors, receipt rates at the CSF and the repository, quantities of UNF and canister types in dry storage, and number of canisters and UNF assemblies that are packaged and re-packaged.

System Facilities Concept Development

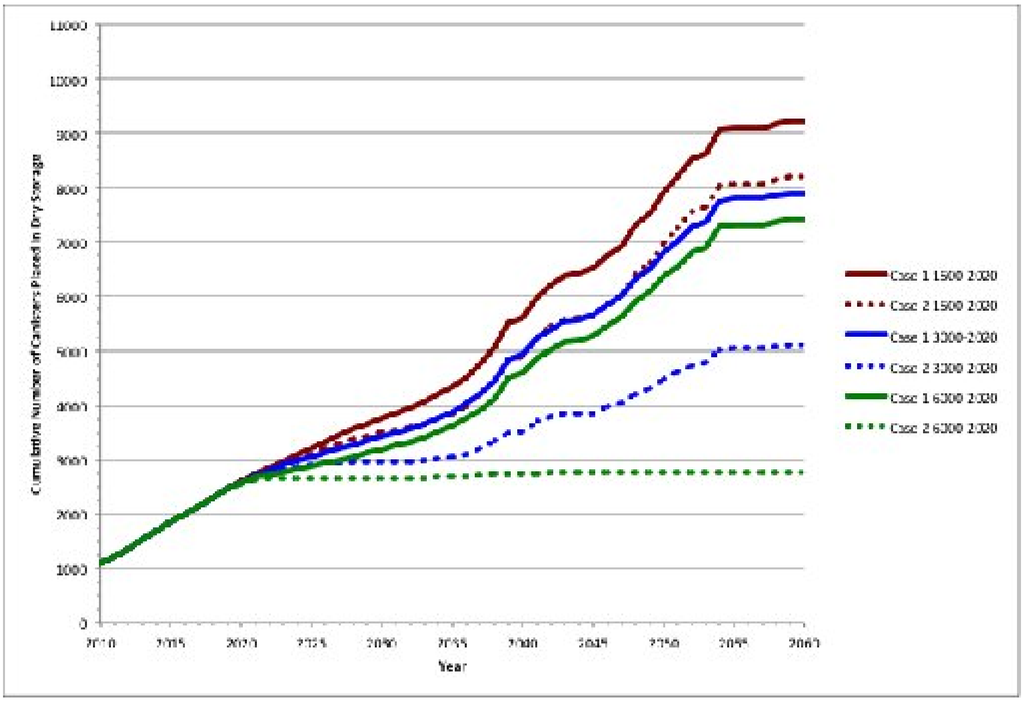
This quantitative logistic information was then used as input to pre-conceptual design development for consolidated storage facilities, packaging/re-packaging facilities and repository surface facilities for use in making rough order of magnitude cost estimates. The CSF design concepts and facility sizes differ depending on the scenario and UNF receipt rates (vertical, horizontal, and bare fuel storage). In addition, the existing legacy and continued use of dual purpose canisters (and single purpose storage casks) must be managed and the inventory and mix of canisters (vertical/horizontal) entering the waste management system depends heavily on the scenario (i.e., UNF acceptance rates and times when facilities come into operation). The inventory mix, the time that UNF transport begins, and the UNF transport rates together dictate the canister and bare fuel receipt rates, directly influencing the CSF and packaging/re-packaging facility design concepts. The strategy for managing UNF in fuel pools once CSF begins operation also affects the design concepts for the CSF and packaging/re-packaging facility. [5]

DISCUSSION/EXAMPLE RESULTS

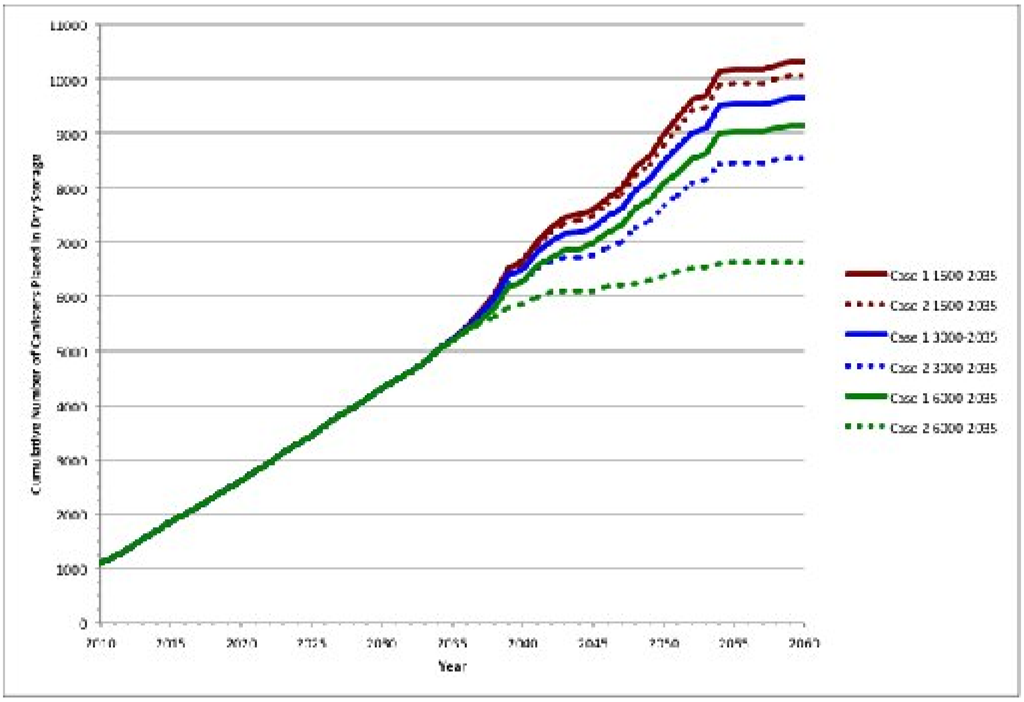
Figure 2, which shows the cumulative number of canisters placed into storage at the reactor sites as a function of time for each of the acceptance scenarios, demonstrates the sort of insights that can be gained from this analysis. This figure reveals a very important difference between the scenarios in which all UNF is placed in existing-size storage canisters at reactor sites before it is moved to a CSF or the repository (Cases 1 and 3) and those in which the bare fuel is removed from reactor pools and shipped to the CSF or the repository (Cases 2 and 4). For each acceptance rate and start date, more fuel is placed into dry storage at the reactor sites in the canister only scenarios (Cases 1 and 3) than in the bare fuel plus canister scenarios (Cases 2 and 4). While the expectation for the canister-only cases was that each reactor's annual allocation would be loaded from the pool into an existing-size storage canister and shipped directly to the CSF or the repository, this proved not to be possible in a significant fraction of cases because of thermal loading constraints that prevented immediate shipment of the casks. Specifically, the maximum thermal load allowed for transportation is lower than the maximum load for storage. For Cases 2 and 4, at a 3000 MTHM/y acceptance rate, a significant amount of fuel residing in the pools does not meet the thermal limits on the storage canister transportation overpacks and cannot be shipped off-site. In such instances, the model selects cooler canisterized fuel that is already in dry storage to be shipped off-site and, in order to maintain pool capacity, loads an equal amount of fuel from the pools into canisters that are stored onsite until they in turn are cool enough to be transported. In these cases, two operations are required at the reactor: (1) loading a new Dual Purpose Caniser (DPC) and placing it in storage on-site, and (2) removing an old storage canister from storage and preparing it for shipment offsite.

In contrast, in the bare fuel scenarios (Cases 2 and 4), if the characteristics of the spent nuclear fuel projected for shipment exceeded the capabilities of one of the bare fuel transportation casks, it was assumed that the cask's capacity is reduced (de-rated) for the affected shipments. This increases the number of individual cask shipments that are required to move the amount of fuel that could be placed in an ESC within acceptable thermal limits, but avoids the additional dry storage at reactor sites that would be required to age that canister until it would meet transportation thermal limits.

The impact of these thermal considerations on the number of canisters that must be stored at reactor sites before they can be moved in the all-canisters cases is not small. For example, Fig. 2 shows that if acceptance starts in 2020 at a 3000 MTHM/y acceptance rate, approximately twice as many additional canisters are stored at reactor sites in the canister-only case than in the bare fuel case. In fact, the 3000 MTHM/y acceptance rate, canister-only case performs only marginally better than the 1500 MTHM/y acceptance rate bare fuel case in terms of ability to limit the increase in on-site canister storage.



(a) 2020 Start of Acceptance



(b) 2035 Start of Acceptance

Fig. 2. Cumulative number of canisters placed in dry storage at reactors.

CONCLUSIONS

This effort re-established an important, foundational capability to assess potential UNF management options. Key insights from the initial analyses include the following.

Higher throughput rates lead to larger facilities. There is a trade-off between higher acceptance/throughput rates and facility size requirements throughout the system. Higher acceptance rates result in reduced at-reactor storage requirements, but larger facilities down-stream in the waste management system. A large UNF acceptance rate, 6000 MTHM/y, showed only incremental benefit in reducing on-site storage, but resulted in the largest facility requirements downstream.

A large acceptance rate, on the order of 6000 MTHM/y may result in under-utilized facilities and may not be cost-effective. The analysis of a 6000 MTHM/y acceptance rate, which is twice the acceptance rate that has been assumed for the waste management system for decades, shows that such a high rate may not be cost effective in the long term. Even though it removes fuel from reactor sites more quickly, and thereby reduces the costs of at reactor storage, it requires heavy expenditure up front in both transportation capacity and receipt capacity at the CSF. The full capacity can only be used for a relatively short time at the beginning of operation of the system until thermal constraints on the fuel available for shipment restricts the achievable acceptance rate to a rate matching UNF discharge from the reactors (around 2000 MTHM/y). It is worth exploring rates in the area of 4000-4500 MTHM/y to determine if some of the benefits of an increased acceptance rate can be achieved without the spikes in UNF shipments that occur and under-utilization issues observed in the 6000 MTHM/y acceptance scenarios.

A large-scale bare UNF handling effort will be needed regardless of the UNF management strategy, acceptance rates, and acceptance start dates. There will always be a need to re-package large canisters unless the direct disposability of such canisters is shown to be feasible. Approximately 11,200 canisters will have to be re-packaged if all UNF is placed in such canisters. Maintaining some fraction of the UNF as bare fuel at central storage facilities can reduce the number of canisters that would have to be repackaged. However, placing the entire UNF inventory in large canisters does not appear to require an increase in the packaging/re-packaging facility capabilities versus maintaining some fraction of the UNF as bare fuel. In addition, the capability to store bare fuel in addition to storing UNF in canisters would be required. There could also be broader system-level impacts associated with maintaining a fraction of the UNF as bare fuel that have yet to be evaluated (e.g., worker dose). Any potential benefit of not having to re-open canisters diminishes for lower acceptance rates and/or delay in the start of acceptance.

Smaller waste package sizes have a significant impact on packaging/re-packaging facility and transportation system requirements. Processing a large number of smaller disposal canisters could result in the need for larger packaging/re-packaging facilities and a larger transportation infrastructure to meet the desired system throughput. Future work investigating alternative disposal canister/overpack and transportation equipment design concepts may identify more efficient concepts.

Bare fuel storage in used fuel pools at a CSF will likely lead to high CSF and overall system life-cycle costs. Future analyses of scenarios involving CSF storage of bare UNF should investigate alternative bare fuel storage concepts (such as dry storage vaults or single-purpose bolted lid bare UNF storage casks).

At-reactor operational and logistic constraints could affect the actual rate that UNF could be loaded into dry storage canisters or transported off-site. Logistic analyses typically assume that there are no constraints on the ability of the reactor sites to load dry storage systems or transport UNF off-site. These assumptions could potentially be challenged while a reactor is in operation due to multiple requirements and demands on the used fuel pool during and operating fuel cycle. Such demands include receipt of fresh fuel, core re-load, fuel inspections/repair, and maintenance of the spent fuel pool. The actual window where fuel handling could occur may constrain the amount of used fuel that could be transferred to dry storage when either multiple fuel handling activities occur within a given operating fuel cycle (transfer to dry storage and loading for shipping off-site) or potentially when smaller capacity canisters are loaded (waste package compatible-size canisters). These constraints should be further explored and their impacts on at-reactor logistics evaluated.

The start of UNF acceptance from the reactors and the UNF acceptance rate will impact on-site dry storage requirements. The analysis shows that there is a significant decrease in the maximum amount of at-reactor dry storage required when the acceptance rate increases from 1500 MTHM/y to 3000 MTHM/y. However, there is a much smaller reduction in the maximum at-reactor dry storage capacity required when the acceptance rate is increased from 3000 MTHM/y to 6000 MTHM/y.

Higher acceptance rates (3000 MTHM/y, 6000 MTHM/y) may not eliminate the need for additional on-site dry storage when reactor fleet begins to shut down unless acceptance is “managed.” A youngest-fuel-first acceptance preference will still require additional dry storage when reactors shut down. An OFF acceptance preference would require additional dry storage both during reactor operation and when the reactors shut down as preference would be given to shipping UNF already in dry storage from the reactor sites.

An OFF acceptance preference would also require continued at-reactor dry storage. Generally, older fuel is the first UNF loaded into dry storage and would be the first shipped under such an acceptance preference. Since little fuel would be shipped directly from the used fuel pools, the reactors would have to transfer fuel from the pools to dry storage to maintain pool capacity.

Acceptance start date and acceptance rates can reduce flexibility. Lower UNF acceptance rates or delay in start of acceptance results in more UNF being placed into existing large canisters for at-reactor dry storage. This “hardens” this “boundary condition,” resulting in reduced flexibility later.

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 as discussed above. 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 cool sufficiently and it can be transported.

Thermal limits for geologic disposal design concepts could also require extended decay storage and/or the blending of UNF during packaging/re-packaging, potentially impacting when UNF could be shipped to a repository or how it is managed at the CSF or repository.

The implications of these thermal constraints and potential UNF management alternatives should be evaluated further.

Acceptance priority assumptions have a significant impact on the UNF management system. The management of UNF at the reactor sites defines the “boundary condition” to which the system will respond. The acceptance priority assumptions, rates, and start dates assumed for this evaluation have a very significant impact on the transportation system and on the sizing of facilities. The preliminary analyses presented here suggest that there would be value to examining modifications to the acceptance priorities that would smooth out some of the sharp peaks and fluctuations that result from strict adherence to simple but rigid priority rules.

Alternate strategies for acceptance from reactors and subsequent shipment to a repository may allow for optimization of down-stream facilities. This initial evaluation assumed first-in-first-out shipping of UNF from the CSF to the repository. It is unlikely that the waste management system would be operated in this manner. A CSF could be treated as an integrated UNF management facility to act as a buffer between at-reactor UNF management needs and future repository requirements. This would allow for optimizing shipments from reactors to minimize additional on-site dry storage requirements and optimizing shipments from the CSF to the repository to meet repository requirements while minimizing processing facility requirements.

In addition, a managed UNF acceptance rate, perhaps giving preference to removing fuel from sites that are either shutdown or approaching shutdown, could potentially reduce long-term at-reactor dry storage requirements.

System benefits may also be gained by de-coupling acceptance rates from the reactors to a CSF with shipping rates between the CSF and a repository. For example, a shorter emplacement period with a higher emplacement rate at the repository than the acceptance rate from the reactors to the CSF combined with a later repository start could result in a large inventory of spent fuel at the CSF that could be more efficiently processed when the repository begins operating.

Such approaches may require additional CSF storage capacity. Additional evaluation of these approaches is needed.

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