

SPENT NUCLEAR FUEL RECEIPT RATE ANALYSIS WITHIN AN INTEGRATED WASTE MANAGEMENT SYSTEM ARCHITECTURE THAT INCLUDES CONSOLIDATED STORAGE

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ABSTRACT

A key parameter in analyzing the performance of an integrated waste management system (IWMS) architecture for the disposition of spent nuclear fuel (SNF) is the SNF receipt rate from reactor and other custodian sites. Receipt rate in this paper means how much SNF is accepted per year for transport in the IWMS from such sites. Introducing one or more federal consolidated storage facilities (CSFs) into the IWMS architecture can potentially accelerate the receipt rate profile over time relative to system architectures without a CSF. This raises the question of what an optimal SNF receipt rate profile for an IWMS architecture might be in view of practical constraints and desired system performance attributes and associated metrics. This paper describes a sensitivity study on SNF receipt rates and the associated results for a selected set of IWMS scenarios aimed at informing near-term planning for storage capabilities and transportation assets. Two different strategies for CSF operation while awaiting availability of a disposal system to receive SNF are compared: one that relatively quickly fills an initial CSF and then idles the transportation system; and another that aims for more continuous use of transportation assets and receipt capabilities at the CSF. This study examines cost considerations and other factors, such as the timing of clearing reactor sites of SNF, efficient use of capital assets, and some other metrics that might be important to a CSF host community. Based on the analysis, an initial approach is presented that targets a continuous receipt strategy while maintaining the flexibility to step up receipt capabilities to a reasonable degree when needed and beneficial, within overall system constraints.

INTRODUCTION

The commercial spent nuclear fuel (SNF) inventory in the United States increases annually by about 2,200 metric tons of heavy metal (MTHM) and is estimated to total approximately 95,000 MTHM at the end of 2024 [1]. Excluding a relatively small amount at U.S. Department of Energy (DOE) sites, this commercial SNF inventory is spread across 74 operating or shutdown nuclear power plants and an away-from-reactor independent spent fuel storage installation (ISFSI) [2]. DOE is planning for the transportation, storage, and ultimate disposal of the SNF and high-level waste (HLW) inventory in the United States. Toward this end, the DOE is applying knowledge and understanding from systems engineering to inform the decision-making process on pathways for safe and secure management of SNF and HLW through disposal. These efforts are being led by the Office of Spent Fuel and High-Level Waste Disposition within the Office of Nuclear Energy.

To aid in this analysis, DOE has sponsored the development of the Next Generation System Analysis Model (NGSAM), a tool that was designed to answer “what if” questions related to SNF and HLW management [3–5]. This tool is an agent-based discrete event simulation toolkit that was designed to handle the back end of the fuel cycle from when a fuel assembly is discharged from a reactor to when the SNF is disposed of in a deep geological repository. This tool tracks each management step that the SNF fuel assembly undergoes, individually such as

loading it into a canister or collectively with other SNF assemblies such as unloading an SNF cask from a railcar. There are three major systems that support back-end SNF and HLW management: storage, disposal, and transportation. Together these three systems form the integrated waste management system (IWMS). Each system can be thought of as an independent entity that interacts with the other systems. A conceptual model of the IWMS depicting the integral overarching systems is shown in Figure 1.

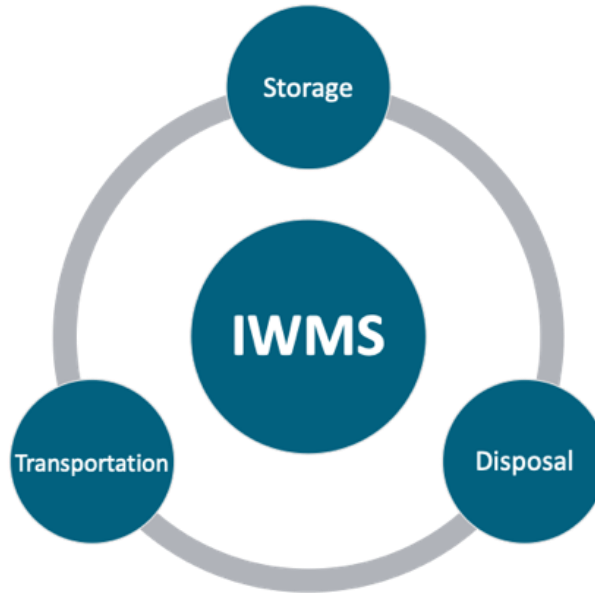


Figure 1. Major systems integral to the IWMS [6].

This paper initially describes the functionality and capabilities of the NGSAM tool. This includes the typical analyses performed by the analyst, data sources used by NGSAM, and the execution mechanism available in the tool. This is followed by describing the scenarios of interest with respect to the SNF receipt rates. In this work, the following receipt rates of interest will be explored: 1,500, 3,000, and 4,500 MTHM per year. In addition, a special scenario where the receipt rate changes midway from 3,000 to 4,500 MTHM per year will be covered. The underlying assumptions, scenario setup, and the major results will be studied. A comprehensive comparison between the scenarios will be provided that summarizes the results and demonstrates the impact of receipt rates on the IWMS.

NEXT GENERATION SYSTEM ANALYSIS MODEL (NGSAM)

As mentioned previously, NGSAM is a tool used to model the back end of the fuel cycle. This tool was developed by Argonne National Laboratory (ANL) with support from analysts at Idaho National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories. This tool was initially based on a logistical analysis tool called Process Analysis Tool that was used by the Department of Defense and Federal Emergency Management Agency to perform system-level modeling. There are several parameters that can be varied on the back end of the fuel cycle, for instance, assumed facility startup dates, future canister and cask types used, shipment rates, shipping logic, etc. The aim of NGSAM is to provide the analyst with the capability to model various potential scenarios for back-end SNF management. The resulting data, covering a wide range of scenarios, are anticipated to aid decision-makers in the decision-making process of managing the SNF and HLW inventory in the United States.

To perform these complex studies, the NGSAM tool requires a broad range of input data. Most of the data for running NGSAM come from three sources: DOE's STANDARDS SNF data and analysis tool, formerly known as UNF-ST&DARDS, DOE's Stakeholder Tool for Assessing Radioactive Transportation (START), and scenario data inputs from the analyst [7, 8]. The data pertinent to the SNF, such as assembly-level heat generation, come from STANDARDS. Transportation of SNF can be modeled from the reactor sites to a consolidated storage

facility (CSF) or other destination site. The START tool provides transportation data, such as the distance between the origin and destination as well as the railroad track class. Each railroad track class has a corresponding maximum speed that can be supported, which is available in the START tool. However, NGSAM is not constrained to using this data provided by the START tool. Instead in NGSAM, the analyst has the flexibility to change the maximum speed allowed on each railroad class, and similar provisions are provided for barge and highway shipments as well. This provides the analyst with a high level of flexibility in modeling the system. The START tool has its own development team, and each version of START is also subjected to a robust verification and validation routine before being deployed in a production environment [9–11]. The last source of data is the systems analyst. This analyst is responsible for determining scenario-specific inputs like hypothetical locations of facilities for the purposes of determining transit distances, the acquisition profile for casks and rolling stock, the operational hours for a given facility, and various timing profiles that determine the amount of time it takes to load and unload casks from a railcar as well as the time it takes to extract canisters from casks. NGSAM can be executed either locally on the analyst's computer or on the NGSAM server deployed at ANL. Running scenarios on the NGSAM server is preferred due to the vast computational resources required by the scenario.

As for the transportation aspects, rail is the preferred mode of transportation for moving SNF in the United States due to size and weight of as-loaded SNF containers. Some commercial SNF casks can weigh over 200 tons; however, the legal weight limit for trucks in the United States is 40 tons [12]. From this standpoint, rail is preferred over highway shipment (at a system level). Barges have the capability to handle the weight of these casks, but railroads have a relatively widespread network compared to navigable waterways in the United States. Therefore, out of the three modes of transportation, rail is the preferred option for large-scale SNF transportation operations.

The process steps involved in modeling dual purposes canister-based systems is explained. At the start of the scenario, all the empty transportation casks and the rail consist start from the fleet maintenance facility (FMF). A combination of cask car(s), buffer cars, and a rail escort vehicle is called a rail consist. The FMF is generally assumed to be co-located with the destination site in current scenarios to simplify the analysis and improve operational efficiency. The rail consist departs from the FMF to the origin site. At the origin site, the SNF is loaded into transportation overpacks, and the consist departs for the destination site. At the destination site, the transportation overpacks are unloaded from the rail car, and the canister is extracted and transferred to a storage cask. The empty transportation overpack is loaded back onto the railcar. Optional maintenance activities can be performed on the transportation overpacks, or the rail consist at this point. At the end of all these activities, one trip is completed in NGSAM, and the rolling stock is available for the next trip. Most of the reactor sites in NGSAM have rail as a mode of transportation. In some scenarios, a rail line might not be available or operable at the reactor site. In these situations, the fuel is loaded at the reactor site using heavy haul trucks and/or barges. The fuel is then transferred onto the rail consist at a transload site. From the transload site, the rail consist departs for the destination site where the transportation overpack is unloaded, the canister is extracted, and the empty transportation overpack is loaded back onto the railcar. Figure 2 shows the process flow of a shipment within NGSAM.

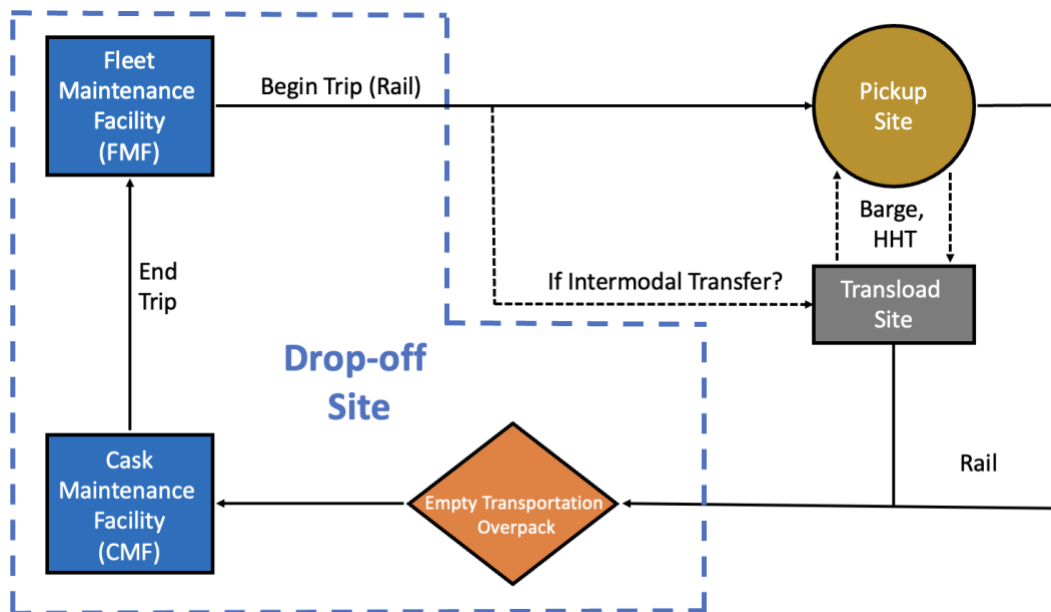


Figure 2. An overview of a transportation trip in NGSAM

RECEIPT RATE ANALYSIS FOR AN IWMS WITH A CSF

SNF receipt rates at facilities within an IWMS play an important role in determining how those facilities will be designed and operated. A CSF within an IWMS is anticipated to be operational for several decades depending on the specific needs that are being addressed. In this work, we will explore the implications of varying the receipt rates of a federal deep geologic repository (DGR) and a CSF on the IWMS. The following steady-state shipping rates from reactor sites are explored: 1,500, 3,000, and 4,500 MTHM per year, initially to a CSF and subsequently to a DGR. These three scenarios are referred to as sequential shipping scenarios in this paper because once a DGR becomes fully operational, shipments to a CSF cease and priority is given to clearing reactor sites of SNF, after which shipments from the CSF to the DGR take place to clear the CSF of SNF. In addition to these scenarios, a fourth scenario is also explored in which shipping SNF from the CSF to a DGR takes place concurrently with shipping SNF from reactor sites. In this fourth scenario, a CSF initially receives SNF from reactor sites at 3,000 MTHM/year. After a DGR having 4500 MTHM/year SNF receipt rate capability becomes operational, the DGR is used to maintain the steady-state shipping rate of 3,000 MTHM/year from reactor sites, while also receiving 1,500 MTHM/yr from the CSF. This fourth scenario with concurrent shipping and a DGR with 4,500 MTHM/yr receipt commercial SNF receipt capability will be compared to the 4,500 MTHM/yr sequential shipping scenario in this paper.

For the comparison of the concurrent and sequential scenarios at 4,500 MTHM/yr DGR receipt rate, it is important to define a few metrics that are planned to be reported for each of these scenarios. These include:

- The relative total cost for each scenario normalized to the 4,500 MTHM/year sequential scenario, and the contributions to total cost associated with management of SNF at reactor sites, the CSF, and in the transportation system.
- Estimated number of transportation assets acquired (i.e., casks, railcars, buffer cars, and rail escort vehicles)
- Number of years the CSF is in an idle state from a shipment perspective (neither receiving nor shipping SNF)
- The time it takes to clear all reactor sites and the CSF of SNF, and the number of reactor sites cleared as a function of time
- The utilization factor for railcars over the course of the scenarios.

Now that the scenarios and the metrics are defined, the next step is to understand the common assumptions that are used to run these scenarios in NGSAM. Each time a scenario is run in NGSAM a detailed set of

assumptions are developed for variables in the scenario; this allows for independent verification of the model by other systems analysts. A few important assumptions for the scenario are detailed below:

- An inventory of ~180,000 MTHM is considered, assuming all reactors operating at the end of 2025 receive a subsequent license renewal (i.e., 80 years of operation).
- A single CSF with maximum storage capacity of 75,000 MTHM and a single DGR with maximum disposal capacity of 180,000 MTHM start operations at the beginning of calendar years 2040 and 2065, respectively.
- A ramp-up rate of 500, 1000, 1500, 2000, 3000, and 4500 MTHM per year was used during the first 6 years of facility start-up before reaching a steady state. When the DGR ramps up, the CSF acceptance ramps down all while ensuring that system accepts 4500 MTHM between the CSF and the DGR.
- An unconstrained rolling stock acquisition profile is used. This means the system is free to acquire infrastructure as required by the scenario without any restrictions.
- An oldest-fuel-first shipping allocation algorithm was assumed for reactor and independent spent fuel storage installation (ISFSI) sites. This means that the order in which SNF shipping opportunities are assigned to sites is based on the order in which the SNF was discharged from reactors.
- A minimum and maximum rail consist size of 1 and 7 cask-carrying railcars, respectively, were used.
- All the SNF inventory does not have to flow through the CSF on its way to the DGR when the DGR is operational.
- The DGR and reactor sites have work shifts that operate for 24 and 8 hours per day when receiving or shipping SNF, respectively. The CSF operates 8, 16, and 24 hours a day for the 1,500, 3,000, and 4,500 MTHM per year shipping rates, respectively.
- A consolidated cask vendor mapping was implemented which assumes that all canisters of a specific vendor can be accommodated by a single transportation overpack from that vendor. This allows for increased cask usage and potential cost savings.

RESULTS

Taking the assumed 180,000 MTHM inventory, DGR and CSF initial SNF receipt dates, and ramp-up rate into account, the number of years for all reactor sites and the CSF to be cleared of SNF is shown in

Table 1 assuming that the final shipments are not constrained by thermal or dose rate limitations.

Table 1. Time to receive all SNF at the DGR assuming 180,000 MTHM of SNF inventory

DGR SNF receipt rate (MTHM/year)	No. of years to receive all SNF once DGR begins receipt	Date of last receipt at DGR and shipment from CSF	No. of years of CSF operation with SNF
1,500	121	2186	146
3,000	62	2127	87
4,500	43	2108	68

If the total inventory is less or the ramp-up to steady state quicker, the number of years for all SNF to be received at the DGR will be less than the values shown in the table. If the gap in time between CSF and DGR startup years is greater than 25 years (assumption), then the number of years of CSF operation with SNF would increase accordingly.

For the comparison between sequential and concurrent shipping scenarios, a 4,500 MTHM/yr DGR case is used for both. Once these scenarios are run, there are several results of interest that can be compared to understand the performance at a system level. As mentioned previously, there are five key metrics (relative

costs, rolling stock, site clearance profile, CSF operational years, and railcar utilization factor) that will be covered as part of this discussion.

In these scenarios, estimated costs are reported for several activities but can broadly be classified as at-reactor, CSF, transportation, and DGR costs. For this study, it is assumed that the DGR costs are the same between the sequential and concurrent shipping scenarios, each having a DGR with receipt rate of 4500 MTHM/year, and thus DGR costs are not included (constant dollar is assumed). Table 2 shows the cost data for the two scenarios normalized to the total cost of the sequential shipping scenario which is set equal to 100.

Table 2. Normalized cost data for the 4,500 MTHM/yr DGR receipt rate scenarios.

Scenario	Sequential Shipping	Concurrent Shipping
CSF Receipt Rate	4,500MTHM/yr	3,000MTHM/yr
Transportation	13.53	13.49
At-reactor	66.40	75.71
CSF	20.08	19.36
Total (excluding DGR)	100.00	108.56

From Table 2, we observe that the transportation and CSF costs between the two scenarios are fairly similar, but the at-reactor costs for the concurrent shipping scenario are higher which can be expected since reactor sites would not be cleared of SNF as quickly due to the lower SNF receipt rate at the CSF. The CSF costs are similar for the sequential and concurrent scenarios since in both the cases the CSF reaches the 75,000 MTHM capacity at which point the CSF costs are similar. From a transportation costs standpoint, the concurrent shipping scenario needs to acquire additional transportation infrastructure to fulfill the 4,500 MTHM/year leading to similar costs. The overall difference in costs, excluding the DGR costs, is that the concurrent shipping scenario with lower CSF receipt rate costs about 8.6% more than the 4,500 MTHM/yr sequential shipping scenario.

The number of nuclear power plant (NPP) and/or ISFSI sites cleared of SNF as a function of time is another important parameter of interest. This directly impacts the at-reactor costs incurred by the system. Figure 3 shows the site clearance profile as a function of year for the sequential and concurrent shipping scenarios. The concurrent shipping takes longer to clear sites because of a lower initial SNF receipt rate for the CSF. The sequential scenario exhibits a long tail at the end of the scenario due to thermal constraints for a small number of casks based on the assumed packaging configuration. For this analysis, there is a total of 75 NPP/ISFSI sites that are considered in the scenarios¹. The years in which 80% of these sites are cleared (60 sites) are 2101, and 2090 for the concurrent and sequential scenarios, respectively. All the sites are cleared by 2128 for the concurrent and sequential shipping scenarios, which is about the same date as that calculated for the 3,000 MTHM/yr scenario in **Error! Reference source not found.** which assumed no technical constraints on the final shipments.

¹ The Nine Mile Point NPP and James A. Fitz Patrick NPP could be considered to be located at a single site due to proximity and site boundary/exclusion area considerations. Also, the Hope Creek NPP and Salem NPP could be considered to be located at a single site due to proximity and shared ISFSI. However, for this analysis, each of these NPPs are modeled separately.

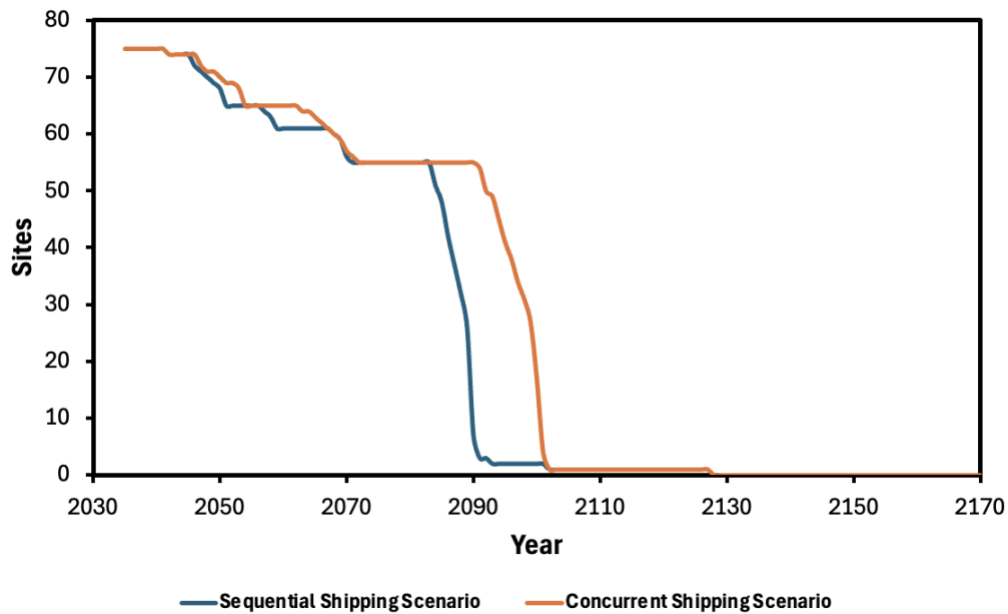


Figure 3. Site clearance profile for sequential and concurrent shipping scenarios

Shipping and receiving activities at a CSF may play an important role from the host community standpoint since they ensure continued activity at the CSF. Table 3 covers the year the maximum capacity is reached at the CSF and the number of years the CSF is idle (no shipping or receiving activities) for the two identified scenarios. The last year for an incoming shipment to the CSF is based on the CSF capacity, shipping rate, and the opening of the DGR. Once the DGR opens, SNF is shipped from the reactor sites rather than the CSF for the sequential shipping scenario. Once all the reactor sites are cleared or nearly cleared, SNF is shipped to the DGR from the CSF. For the concurrent shipping scenario, there is little to no down time between switching from receiving SNF at the CSF to shipping SNF from a CSF to a DGR. The years with no shipping and receiving activity is the difference in years between the first outbound shipment from the CSF and the last inbound shipment to the CSF. The concurrent shipping scenario provides for relatively continuous receiving or shipping operations at the CSF as compared to the sequential shipping scenario.

Table 3. Key CSF metrics for the shipping scenarios of interest.

	Sequential Shipping Scenario with 4,500 MTHM/yr CSF Receipt Rate	Concurrent Shipping Scenario with 3,000 MTHM/yr CSF Receipt Rate
CSF start year	2040	2040
Year of last inbound SNF shipment at CSF	2060	2068
Maximum MTHM at CSF	75000	75000
Year of first outbound shipment from CSF	2091	2069
Number of years with no shipping/receiving activity	30	0

Rolling stock also plays a critical role in achieving the desired shipping rate. It must be mentioned that an unconstrained acquisition profile was used in this work, meaning the system is free to acquire resources at will to accomplish the shipments. This includes both transportation overpacks as well as railcars, buffer cars, and rail escort vehicles. Table 4 presents the results for the scenarios of interest. Both the total infrastructure needed as well as the infrastructure needed to initially achieve the desired shipping rates are captured. The

rolling stock increases as the initial shipping rate increases. The total rail infrastructure is similar for the 4,500 MTHM/yr and the 3,000 MTHM/yr alternative scenario since the shipping rate is the same once the DGR opens.

Table 4. Infrastructure acquisition for the scenarios including infrastructure for the entire scenario and rolling stock required to achieve the desired shipping rate.

Sequential Shipping Scenario		Total	Rolling stock to achieve 4,500 MTHM/year
	Transportation Overpacks	152	63
	Railcars to Carry Casks	73	45
	Buffer Cars	13	8
	Rail Escort Vehicles	26	16
Concurrent Shipping Scenario		Total	Rolling stock to achieve 3,000 MTHM/year
	Transportation Overpacks	133	53
	Railcars to Carry Casks	75	34
	Buffer Cars	13	6
	Rail Escort Vehicles	26	12

Finally, the railcar utilization factor for the scenarios is reported. A railcar is in use if it is in transit, at the reactor site or CSF, or undergoing maintenance. If none of these activities are being performed, the railcar is considered not to be in use. This data in NGSAM is a daily value; therefore, averages per scenario are computed to effectively report the data. Years with no shipments are also considered while computing the average if they happen to occur between the first and last shipment at the site (a conservative assumption). The railcar utilization factor is shown in Table 5. It must be mentioned that an unconstrained acquisition profile was used. This means even if the system needed a railcar for one trip, the infrastructure would be acquired. Constraining the rolling stock acquisition is anticipated to increase the average cask utilization factor at the cost of potentially reducing the number of casks picked up in a year. The table value shows a lower railcar utilization factor for the sequential shipping scenario, which is due at least in part to the idle period at the CSF when the CSF has reached maximum storage capacity, and the system is waiting for the DGR to become operational. It should be noted that the cost table presented earlier does not account for any additional costs which might be related to storage of transportation assets during this period.

Table 5. Railcar utilization factor for the four scenarios of interest.

Scenario	Average Railcar Utilization (%)
Sequential Shipping	41.6
Concurrent Shipping	44.5

CONCLUSION

This work covered the implications of shipping rates on the IWMS involving a federal CSF including examination of shipments from a CSF to a federal DGR that may occur sequentially or concurrently with shipments from reactor sites to a DGR. The scenarios were explored with variable shipping rates and approaches, and their implications on the normalized cost, site clearance profiles, rolling stock acquisition,

CSF shipping/receipt years, and railcar utilization factors were studied. A higher shipping rate, provided it is feasible, results in an ability to clear sites sooner. The concurrent shipping scenario results in minimum CSF downtime (more continuous receipt/shipping operations) and better use of transportation assets while having a cost less than 10% higher than the sequential shipping scenario. These results indicate that it may be prudent to design the CSF for a 4500 MTHM/yr receipt rate capability and preserve the flexibility of operating it at a steady-state receipt rate of 3,000 MTHM/yr or 4,500 MTHM/yr along with the ability to make adjustments to the receipt rate as needed and beneficial over the course of CSF operations. DOE intends to confirm the assumptions in the model through a peer review with industry experienced in SNF cask loading and rail transport operations to clearly define system constraints.

DISCLAIMER

This is a technical paper that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961).

To the extent discussions or recommendations in this paper conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract.

This paper reflects technical work which could support future decision making by DOE. No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

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