TRANSPORTATION OF SPENT NUCLEAR FUEL FROM REACTOR SITES IN THE US – WHAT WILL IT TAKE?

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The Department of Energy (DOE) is laying the groundwork for implementing the Administration's Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste, which calls for a consent-based siting process. Potential destinations for an interim storage facility or repository have yet to be identified. The purpose of this study is to evaluate how planning for future transportation of spent nuclear fuel as part of a waste management system may be affected by different choices and strategies. The transportation system is modeled using TOM (Transportation Operations Model), a computer code developed at the Oak Ridge National Laboratory (ORNL). The simulations include scenarios with and without an interim storage facility (ISF) and employing different at-reactor management practices. Various operational start times for the ISF and repository were also considered. The results of the cost analysis provide Rough Order of Magnitude (ROM) capital, operational, and maintenance costs of the transportation system and the corresponding spending profiles as well as information regarding the size of the transportation fleet, distance traveled (consist and cask miles), and fuel age and burnup during the transportation. This study provides useful insights regarding the role of the transportation as an integral part of the waste management system.

I. INTRODUCTION

The Department of Energy (DOE) is planning for the development of a future transportation system for shipping spent nuclear fuel (SNF) from reactor sites to either a potential interim storage facility (ISF), or a potential repository, or both.

According to the Administration's *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* (further referred to as the Administration's Strategy) published in January 2013 [Ref. 1], pending appropriate authorizations from Congress, a pilot ISF is planned for availability in 2021, with an initial focus on accepting SNF from shutdown reactor sites; a larger ISF is planned for availability in 2025; and a repository is planned for availability in 2048[(1)]. The pilot ISF would receive SNF from shutdown reactors, and the larger consolidated ISF would have greater capacity and capabilities, for example to support receiving SNF from both shutdown and operating reactors. If the Administration's Strategy is able to be implemented as scheduled, the transportation of SNF will begin in 2021.

The first phase of a transportation campaign (i.e., to a pilot ISF) could be conducted over a 4 year period and could target unloading 9 shutdown reactor sites with an inventory of 2,813 MTU. The potential strategies for unloading shutdown reactors and analysis of the site-specific conditions have been considered in a number of publications [Ref. 2, 3, 4, 5, 6, and 7].

The second phase (i.e., to a larger ISF and/or a repository) of the transportation campaign will require a significantly greater effort. With the projected SNF inventory of 140,000 MTU by 2055 [Ref. 8], the remaining SNF inventory in 2055 will be about 137,000 MTU at 65 different locations (62 operating and 3 recently shutdown sites). The transportation of this SNF will be a large-scale campaign spread over at least a few decades.

Developing and operating the large-scale SNF transportation system will most likely present many challenges and will require a long lead time. This task will be complicated by uncertainties such as future SNF management practices and locations of the ISFs and repository.

This study is a part of the ongoing analyses being conducted for the DOE's Nuclear Fuels Storage and Transportation Planning Project. The purpose of this study is to provide an initial high-level evaluation of what it would take to unload all of the reactor sites while accounting for the major uncertainties in the waste management system and using timing assumptions from the Administration's Strategy. The major topics of interest were:

- Rough order of magnitude (ROM) transportation costs.
- Spending profile.
- Transportation fleet requirements.
- Unloading strategy (consist size).
- Distance traveled with loaded casks.
- The age and burnup of fuel and cask heat output during transportation.

This evaluation was not meant to provide specific details or suggest specific options. Rather, it was designed

[1] As noted in the Administration's Strategy, full implementation of this program will require legislation to enable the timely deployment of these waste management system elements. In the meantime, DOE is undertaking activities within existing Congressional authorization to plan for the eventual transportation, storage, and disposal of SNF.

to identify the issues that might be important for planning transportation campaigns in the future.

II. TRANSPORTATION SIMULATION

The analysis was done with the Transportation Storage Logistics (TSL) model [Ref. 9]. TSL is the merger of the existing modeling codes TOM (Transportation Operations Model) [Ref. 10] and CALVIN (CRWMS Analysis and Logistics Visually Interactive tool) [Ref. 9]. The transportation simulations were performed using the TOM component of TSL.

TOM calculates the resources (casks and vehicles) required for meeting the specified pickup scenario, the timing of each trip (its transportation cycle), and all associated capital, operational and maintenance costs. TOM assumes that a consist arrives with empty transportation casks into which the canisters will be loaded, unless the transportation casks exist at the site.

TOM attempts to use a maximum consist size defined by the user. TOM builds as many of the largest-sized consists permitted at the pickup site as possible, and then adds another less-than-maximum-sized consist to move the remaining casks.

The majority of the input parameters used in TOM calculations are defined in the TOM database. These include the locations of the reactor sites, the empty and loaded weight of the casks, the length of time to load and unload the casks, the duration of inspections, the cask and rolling stock costs, and other data required for simulations. The vehicle (train, barge, heavy haul) speeds and the transportation options can be modified by the user as needed.

The pickup schedule is the major input into the TOM calculations. The pickup schedules are generated with the CALVIN component of TSL. CALVIN selects fuel from among the appropriate reactor sites (using a selection algorithm) and then from at-reactor pools and dry storage, that meet site-specific transportation thermal limits starting with the year of the first acceptance at a consolidated storage facility or a repository. The resulting pickup schedule indicates how many casks and what types of casks (if any) need to be picked up from each site during each year while an interim storage facility or/and repository are operational. CALVIN tracks age, burnup, and enrichment of each SNF assembly and its current location in the system. This information can be used to calculate the properties of SNF being transported.

III. TRANSPORTATION SCENARIOS

The transportation scenarios were designed to address the major uncertainties in the waste management system and transportation parameters. Two groups of scenarios (two transportation schemes) were considered: with and without an interim storage facility. These two transportation schemes are displayed in Figure 1. The description of all considered scenarios is provided in Table I. The pickup schedules for these scenarios were generated assuming the consolidated storage facility and repository acceptance rate of 3,000 MTU/yr.

The group A scenarios assume that the SNF will be transported from the reactor sites directly to a repository, which becomes available in 2048, except Scenario A3. Scenario A3 assumes that all of the SNF will be transported to an interim storage facility co-located with the repository starting in 2021. This scenario was intended to show the effects of an extended transportation campaign (2021 to 2098). The transportation campaign in the other scenarios in group A occurs from 2048 to 2098.

The group B scenarios assume that the SNF will be transported from the reactors sites to an interim storage facility starting in 2021 until 2048. Starting in 2048 the SNF will be transported from the reactor sites and from the interim storage facility directly to a repository. All scenarios, except B5, assume that the interim storage facility is in a southeastern location of the U.S. Scenario B5 considers a northwestern location.

The factors analyzed within these two groups of scenarios included the at-reactor fuel management practice; the maximum consist size used in the campaign; the time required for loading and unloading SNF for transportation; and the train speed on the mainline rail.

Two general cases of at-reactor practices were considered. In the first case, it was assumed that the existing dual purpose storage canisters (DPCs) will be loaded at reactor sites until all SNF is transported off site. In the second case, it was assumed that in the future the power plants that still have uncanistered SNF will switch to loading smaller, purpose-designed multi-purpose canisters (MPCs) [(2)]. The MPC definition used here is the same as that used internationally: a sealed canister intended for storage, transport, and disposal. The MPC capacity was assumed to be 12 assemblies for PWR SNF and 32 assemblies for BWR SNF. It was further assumed that a transportation overpack will be designed to transport one MPC.

[2] This is a technical report that does not take into account the contractual limitations under the Standard Contract (10 CFR Pat 961). Under the provisions of the Standard Contract, SNF in canisters is not considered to be an acceptable waste form, absent a mutually agreed to contract modification. To ensure the ability to transfer spent fuel to the U.S. government under the Standard Contract, the individual spent fuel assemblies must be retrievable for packaging into a DOE-supplied transportation cask

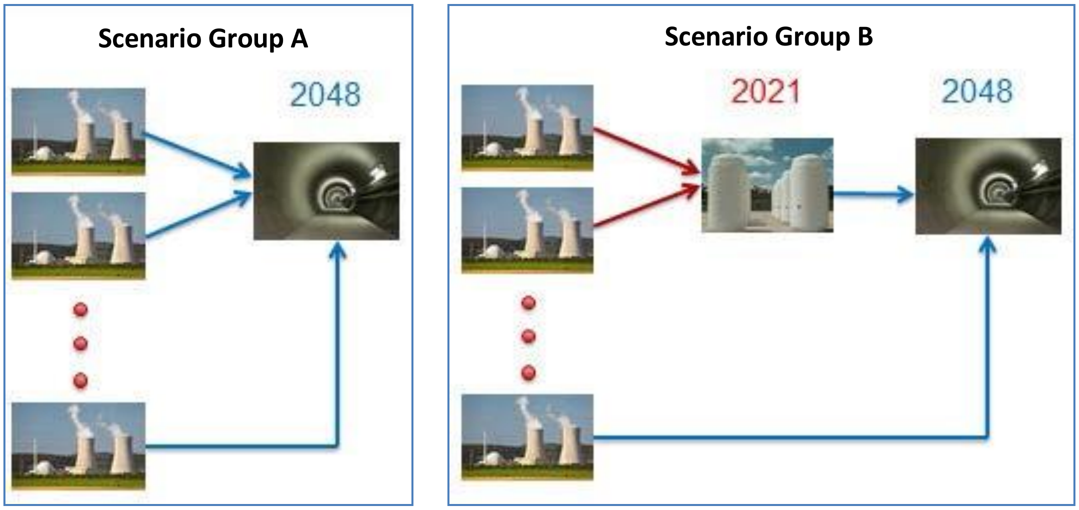


Fig.1. Two Transportation Schemes Considered in the Analysis.

TABLE I. Transportation Analysis Scenario Description.

Scenario Group	Scenario ID	Scenario Parameters				
		Maximum Consist Size	**Loading& Unloading Time**	**Mainline Rail Speed mph**	**Year of Switch to MPCs**	**ISF Location**
A	A1	**3**	original	55	None	N/A
	A1-a	**2**	original	55	None	N/A
	A1-b	**4**	original	55	None	N/A
	A1-c	**5**	original	55	None	N/A
	A1-d	3	**x2**	**55**	None	N/A
	A1-e	3	**x2**	**35**	None	N/A
	A2	3	original	55	**2036**	N/A
	A3	3	original	55	None	**Co-located with repository**
	A4	3	original	55	**2025**	N/A
B	B1	**3**	original	55	None	SE
	B1-a	**2**	original	55	None	SE
	B1-b	**4**	original	55	None	SE
	B1-c	**5**	original	55	None	SE
	B1-d	3	**x2**	**55**	None	SE
	B1-e	3	**x2**	**35**	None	SE
	B2	3	original	55	**2036**	SE
	B3	3	original	55	**2030**	SE
	B4	3	original	55	**2025**	SE
	B5	3	original	55	None	**NW**

The smaller MPC capacity (4PWR/9BWR) was not considered because a few (presumably 4) of these MPCs can be placed in one transportation overpack. As a result, the potential impacts on the transportation should be smaller in the latter case. Scenarios A2 and B2 assumed the switch to MPCs in 2036. Scenarios A4 and B4 assumed the switch to MPCs in 2025. Scenarios B3 assumed the switch to MPCs in 2030.

The maximum consist sizes considered were: 2 cars (A1-a and B1-a); 3-cars (A1 and B1); 4 cars (A1-b and B1-b); and 5 cars (A1-c and B1-c).

The information regarding the time required to load and unload SNF for transportation is specified in the TOM database. The actual time that will be needed for these operations can be different from these values. Longer loading and unloading times may affect the transportation operations because they will lead to longer transportation cycle durations. The same is true for the slower train speeds. Scenario A1-d and B1-d considered double loading and unloading times than the original ones. Scenarios A1-e and B1-e considered both, double loading and unloading times and slower train speed on the mainline rail (35mph instead of 55mph).

IV. TRANSPORTATION ANALYSIS RESULTS

Figure 2 shows the operational (including maintenance), capital, and total costs of the transportation campaign for the two transportation schemes and different at-reactor practices. The choice of at-reactor practice has the largest impact on the total cost. The increase in total cost is mainly due to the increase in the operational costs. This is because switching to the small canisters (MPCs) leads to more trips. The timing of this switch (2025, 2030, or 2036) has a significantly smaller impact. In general, the sooner the switch is made, the more MPCs are loaded and the higher the total cost is. This is true for both transportation schemes, with and without the interim storage facility.

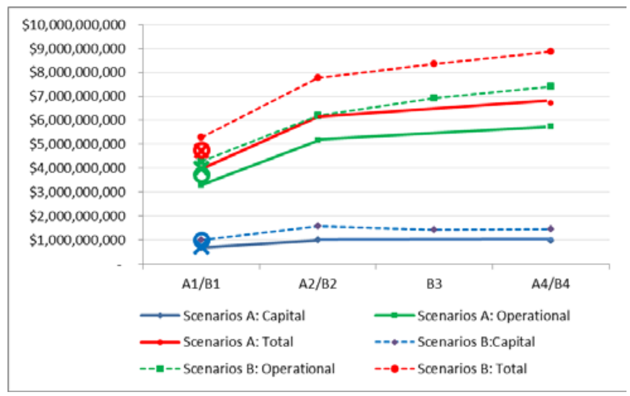
Including an interim storage facility increases the total transportation costs, but the impacts are smaller than the impacts due to the at-reactor practice. The increase in total cost is due to the increase in the operational costs because more trips are required for the scenarios with the interim storage facility.

The additional scenarios shown in Figure 2 are scenario A3 (extended transportation campaign with the consolidated storage co-located with the repository) and scenario B5 (interim storage located in the Northwest U.S.). The impacts from the extended transportation campaign (as compared to scenario A1) and different interim storage facility location (as compared to scenario B1) on the total cost are small.

The capital costs in all the scenarios shown in Figure 2 are similar. This means that the acquisition of the casks and rolling stock is similar as well. The total number of casks that will be required for the transportation campaign and the total number of vehicles, including rail cars, escort cars, and buffer cars, are shown in Figures 3 and 4.

The scenarios without an interim storage facility have very similar acquisitions. This is because the switch to MPCs (2025 or 2036) occurs before the transportation begins (2048). A slightly larger acquisition is required for the MPCs scenarios in the first few years of the campaign to accommodate larger number of canisters. After that, the differences are very small. About half of all the capital costs occur during the first 6 years.

The scenarios with an interim storage facility have some variations in the acquisitions. This is because in the scenarios with MPCs, the additional large acquisitions occur in the year of the switch to MPCs and in the few years following the switch.



NOTE: Large circles show the costs in Scenario A3 and the crosses show the costs in Scenario B5.

Fig. 2. Transportation Costs for the Scenarios with Different Transportation Schemes and at-Reactor Management Practices.

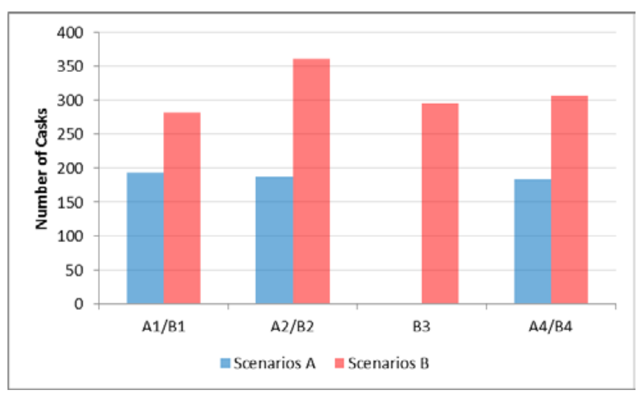


Fig. 3. Cask Acquisition for the Scenarios with Different Transportation Schemes and at-Reactor Management Practices.

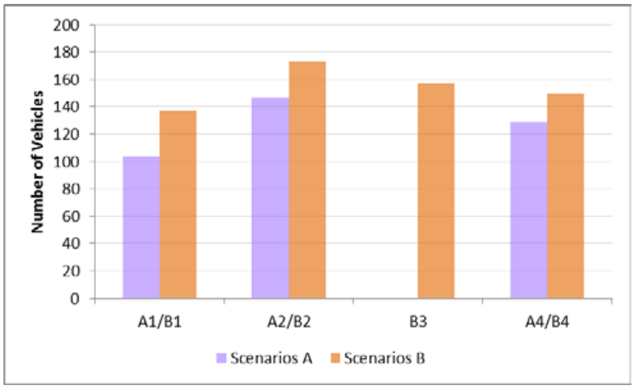


Fig. 4. Vehicle Acquisition for the Scenarios with Different Transportation Schemes and at-Reactor Management Practices.

Figures 5 and 6 show spending profiles for the scenarios with the different transportation schemes. The capital costs calculated in the scenarios without the interim storage facility for the first year of operations was spread over 3 years, which includes the two years prior to operations and the first year of operations. The annual total costs are about two times higher in the scenarios with the MPCs compared to the scenarios in which only DPCs are used in both transportation schemes. The annual total costs are similar in the corresponding scenarios with and without the interim storage facility during 2048-2098 time period. The additional total costs in the scenarios with the interim storage facility are due to the costs incurred during the 2021 to 2048 time period when the transportation from the reactor sites to the interim storage facility takes place.

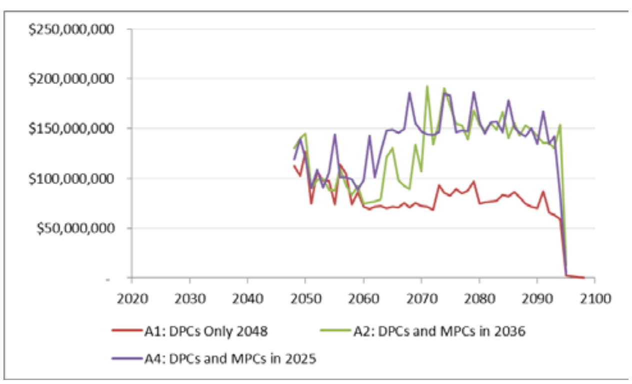


Fig. 5. Spending Profiles for the Scenarios without Interim Storage Facility.

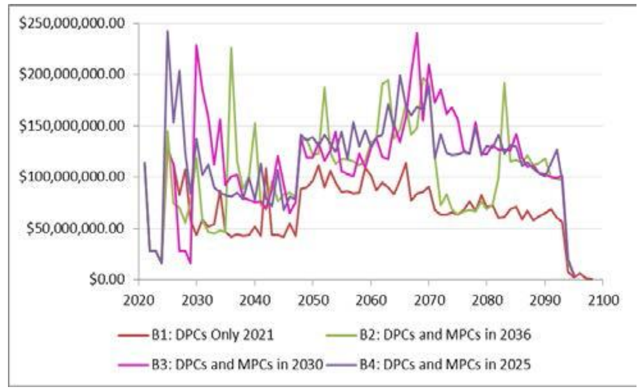


Fig. 6. Spending Profiles for the Scenarios with Interim Storage Facility.

Note that in the scenarios with an interim storage facility the SNF is transported from the reactor sites to the interim storage until 2048. Starting from 2048 (the repository opening date), the SNF from the reactor sites is transported directly to the repository until all reactors are unloaded. In the scenarios considered this occurs in 2071. In all MPCs scenarios, except scenario B2, both DPCs and MPCs are transported from the interim storage to the repository starting from 2071. In scenario B2, only DPCs are transported from 2071 to 2081. The transportation of MPCs begins only in 2082. This results in the annual cost peak shown in Figure 5. This also results in the larger acquisitions required for this scenario (Figures 3 and 4). This is because there are more DPCs in this scenario (late introduction of MPCs) than in the other MPCs scenarios and TSL rules for the interim storage is “first in, first out”.

IV.B. Maximum Consist Size

Using large consists may seem to be an attractive option. Fewer trips will be required to unload the reactor sites and interim storage facility (if applicable). This should decrease the total transportation costs which are driven by the operational costs.

The total transportation cost as a function of the maximum consist size is shown in Figure 7. As expected, the total transportation cost decreases with the increase in the maximum consist size. However, the difference between the scenarios with the different consist sizes are small.

Figures 8 and 9 explain why the variations in the total costs are small. These figures show the number of trips with the different number of railcars for each simulated maximum consist size. Because of the complexity of the pickup schedules, the maximum consist size is achievable in only 74%-77% of the trips for the scenarios with the maximum consist size of 2, 50% to 59% of trips for the scenarios with the maximum consist size of 3, 31% to 42% of the trips for the scenarios with the maximum consist size of 4, and 20% to 31% of the trips for the scenarios with the maximum consist size of 5. The number of trips and the distance traveled do not decrease significantly from the scenarios with the maximum consist size of 2 to the scenarios with the maximum consist size of 5. As a result, the cask miles to consist miles ratio increases only slightly with the maximum consist size. The total costs, consist miles, and the cask miles to consist miles ratios are summarized in Table II.

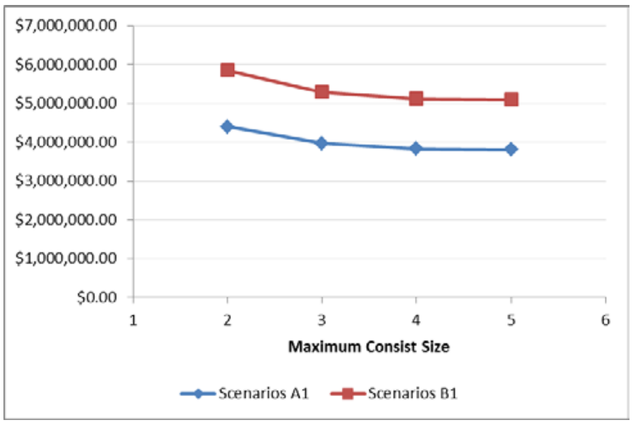


Fig. 7. Total Transportation Cost as a Function of the Maximum Consist Size.

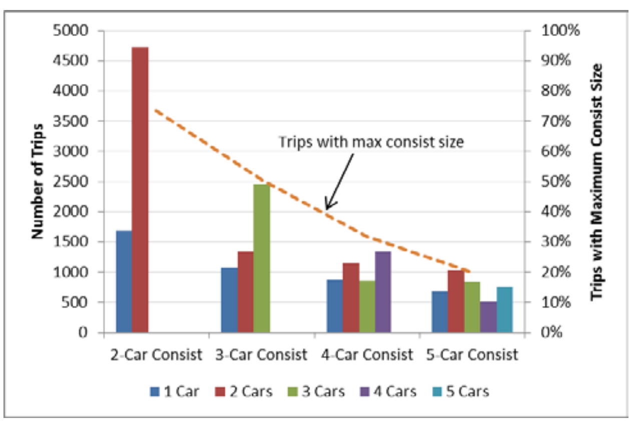


Fig. 8. Number of Trips with the Different Number of Railcars for the Scenarios without the Interim Storage Facility.

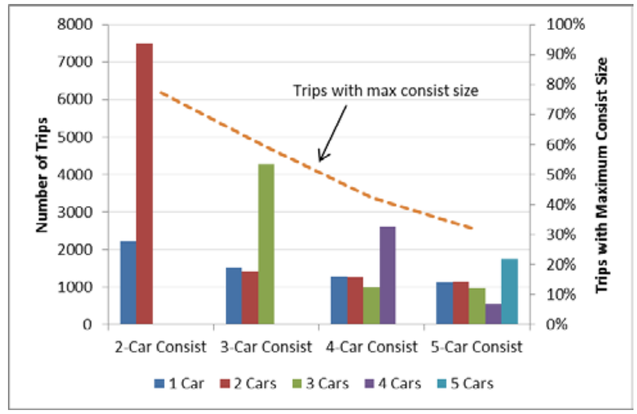


Fig. 9. Number of Trips with the Different Number of Railcars for the Scenarios with the Interim Storage Facility.

TABLE II. Cost and Distance for the Scenarios with the Different Maximum Consist Sizes.

Scenario ID	Max Consist Size	Total Cost $B	Consist Miles	Cask Miles to Consist Miles Ratio
A1-a	2	4.40	3.37E+07	1.73
A1	3	3.97	2.5E+07	2.28
A1-b	4	3.83	2.2E+07	2.61
A1-c	5	3.80	2.0E+07	2.87
B1-a	2	5.52	5.5E+07	1.77
B1	3	5.29	4.1E+07	2.39
B1-b	4	5.12	3.5E+07	2.81
B1-c	5	5.09	3.1E+07	3.13

IV.C. Loading and Unloading Time and Train Speed

The total transportation costs for the scenarios with the different loading and unloading times and train speeds are summarized in Table III. The train speed has little impact on the transportation costs. This is consistent with the conclusions made in [Ref. 8]. This reference provides a more detailed analysis of the train speed impacts on transportation, and it concludes that the impacts are negligible.

TABLE III. Total Costs for the Scenarios with Different Loading and Unloading Times and Train Speeds.

Scenario ID	Scenario Description	Total Cost, $B	% Increase in Total Cost
A1	Original loading (unloading) time and train speed	3.97	-
A1-d	2xloading (unloading) time	4.09	1.2
A1-e	2xloading (unloading) time and 35 mph train speed	4.1	1.3
B1	Original loading (unloading) time and train speed	5.29	-
B1-d	2xloading (unloading) time	5.57	2.8
B1-e	2xloading (unloading) time and 35 mph train speed	5.6	3.1

The impacts from loading and unloading times are greater compared to the train speed, but small compared to the other factors considered in this analysis. A two-fold increase in loading and unloading times results in a 1% to 3 % increase in the total transportation costs.

IV.D. Average SNF Age, Burnup, and Canister Heat Output during the Transportation

Figures 10 through 12 show the SNF average age, burnup, and canister heat output during the transportation for each year of the transportation campaign for the two transportation schemes (with and without an interim storage facility). The scenarios in these figures are the ones in which only DPCs are loaded at the reactor sites.

In the scenario without an interim storage facility the average SNF age during the transportation gradually changes from 66 years old at the beginning of the campaign to 45 years old at the end of campaign. By 2048 about 85% of SNF at the reactor sites is in dry storage canisters. As a result, the SNF loaded for transportation mostly comes from the dry storage. This explains the gradual transition from older to younger fuel. As the fuel becomes younger, its burnup becomes higher (Figure 11). The canister heat output during most of the campaign is 10kW or less.

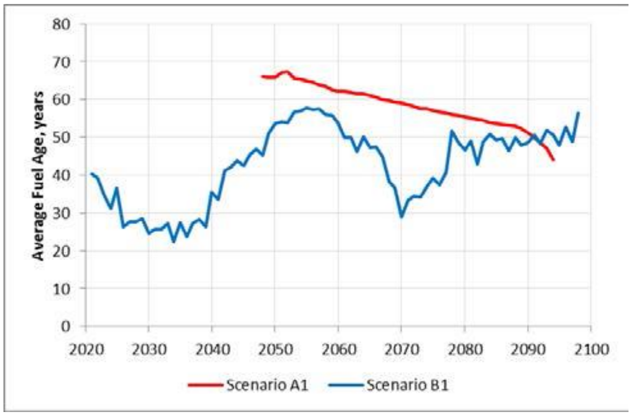


Fig. 10. Average SNF Age during Transportation.

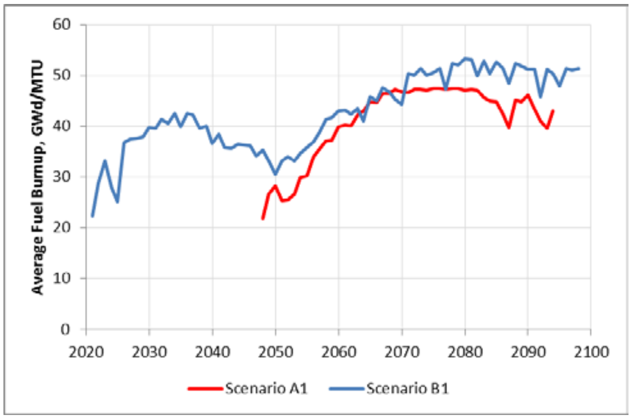


Fig. 11. Average SNF Burnup during Transportation.

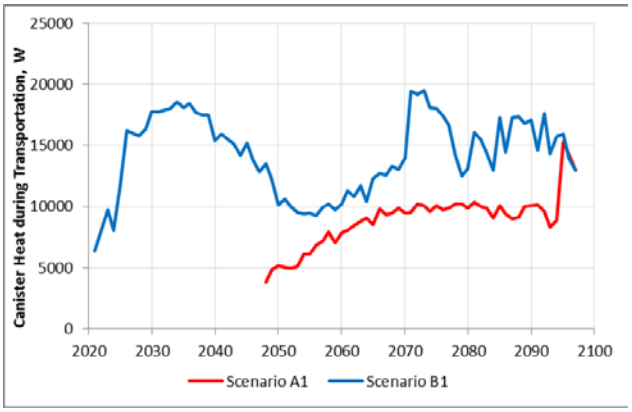


Fig. 12. Average Canister Heat Output during Transportation.

In the scenario with the ISF the age, burnup, and canister heat output profiles are more complex. The fuel age is 20 to 40 years old during the first 20 years of campaign and is around 50 years old during the last 20 years of the campaign. The age increases and then decreases during the middle part of the campaign. This is because at the beginning of the transportation campaign young fuel with higher burnup comes from the pools at the reactor sites. Later in the campaign, the fuel comes mostly from dry storage, and during this period of time the age, burnup, and heat output profiles resemble the profiles calculated for the scenario without the interim storage facility.

V. CONCLUSIONS

A large-scale transportation campaign spread over at least a few decades will be required to remove SNF from the reactor sites. The design of such a campaign will present a significant challenge due to many uncertainties associated with the future state of the waste management system. Some of these uncertainties will not be resolved for a long time. The purpose of this study was to identify the issues that might be important for planning transportation campaigns in the future. The major findings of this transportation analysis are summarized below.

The total cost of the transportation campaign is mainly a function of the operational costs due to a large number of shipments. Consequently, the transportation scenarios that require more trips will have a higher total cost. In this analysis, the scenarios that required significantly more trips and had the higher total costs were: (1) the ones in which the small canisters (MPCs) were used at the reactor sites and (2) the ones that included the interim storage facility. In the scenarios considered, the impacts on the total cost from using the small canisters were greater than the impacts from including the interim storage facility. The ROM total transportation cost ranged from $4B to $9B.

The hardware acquisitions required to conduct the transportation campaign and the corresponding capital costs are less affected by the scenario parameters. In the scenarios considered, the total number of casks ranged from 183 to 361, the total number of vehicles ranged from 104 to 173, and the capital costs ranged from $0.7B to $1.6B.

The differences in the spending profiles mainly reflect the differences in the operational costs. In the scenarios considered, the average annual costs ranged from $80M (scenarios with DPCs only) to $130M (scenarios with MPCs). More evenly distributed spending profiles can be achieved if the capital costs are spread across a few years prior to the year in which the acquisition is actually needed.

The factors such as the location of an interim storage facility, the duration of the transportation campaign, maximum consist size, train speed, and loading and unloading times have small impacts on the transportation costs.

It was shown that the pickup schedule is complex and requires 1- and 2-car consists even if the larger consist size is attempted. The smaller consists will be more flexible with regard to the rail conditions, such as weight limitations on the bridges and the storage space at the loading sites. A maximum consist size of 3 appears to be optimal. With a maximum consist size of 3, 50-60% of the trips used 3-car consists, 20-27% of the trips used 2-car consists, and 21-22% of the trips used a 1-car consist.

The average fuel age, burnup, and canister heat output during the transportation campaign will change over time. The age, burnup, and heat profiles will depend on the amounts of fuel loaded for transportation from pools and dry storage. Assuming the transportation campaign begins in 2021, the average fuel age will be 20 to 40 years old during the first 20 years of campaign, 50 years old during the last 20 years of the campaign, and from 30 to 60 years old in the middle of the campaign. The younger fuel will have higher burnup and higher canister heat output.

It should also be noted that this study only considers the costs associated with transportation. This study does not include consideration of costs associated with the ISF and/or repository, nor does it consider any costs or impacts under the Standard Contract that DOE has in place with nuclear utilities. The cost associated with transportation is only one of many attributes that should be considered in the decision analysis. For example, the use of MPCs significantly increases the transportation costs; however, should the use of such canisters allow for direct disposal at a repository, then not having to repackage the SNF could result in a much greater cost reduction for the operation of the overall system.

ACKNOWLEDGMENTS

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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