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

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The Department of Energy (DOE) is responsible for developing and implementing a transportation system for shipping spent nuclear fuel (SNF) from the reactor sites to either a potential consolidated storage facility (CSF), or a potential repository, or both. The DOE's Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste published in January 2013 calls for a consent-based siting process. This means that multiple candidate locations and numerous CSF/repository concepts will be considered, evaluated, and compared. The purpose of this study was to evaluate how the transportation component of the waste management system will be affected by the different choices and strategies. The transportation system was modeled using TOM (Transportation Operations Model), a computer code developed at the Oak Ridge National Laboratories (ORNL). The scenarios with and without CSF and different at-reactors management practices were simulated. A few different possible times of when the CSF and a repository become operational were considered. The logistic results of this analysis provided the information regarding the size of the transportation fleet and the time during which it has to be acquired; number of trips and duration of each trip, and consist and cask miles. The results of the cost analysis provided the Rough Order of Magnitude (ROM) capital, operational, and maintenance costs of the transportation system and the corresponding spending profiles. The total cost of transporting SNF from the reactor sites to a potential repository was evaluated for each scenario. These transportation costs were compared to the total (except the waste disposal) costs of the waste management system. 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 responsible for developing and implementing a transportation system for shipping spent nuclear fuel (SNF) from the reactor sites to either a potential consolidated storage facility (CSF), or a potential repository, or both. The SNF has been transported world-wide during the past 40 years. However, the transportation in the US has been limited to the shipments of the radioactive materials by the nuclear industry, the Naval Nuclear Propulsion Program (NNPP), and DOE transuranic waste shipments to WIPP.

According to the DOE'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], a pilot interim storage facility will be available in 2021, a larger interim storage facility will be available in 2025, and a repository will be available in 2048. The pilot storage facility will receive SNF from the existing shutdown reactors and the larger storage facility will receive SNF from both, new shutdown and operating reactors. If this strategy is implemented as scheduled, the transportation of SNF will begin in 2021.

The first (pilot storage facility) phase of transportation campaign will be conducted over the 4 year period and will target unloading the 9 old shutdown reactor sites with the inventory of 2,813 MTU. The potential strategies of unloading shutdown reactors and analysis of the site-specific conditions were considered in a number of publications [Ref. 2, 3, 4, 5, 6, and 7].

The second phase (a larger storage facility and 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 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.

Designing large-scale transportation of SNF will most likely present many challenges and will require long lead time. This task will be complicated by the significant uncertainties regarding the current and future states of waste management system, future SNF management practices and legislation environment, locations of the consolidated storage facility and repository, and new entity (the MDO) that will be responsible for the waste management, including transportation. Some of these uncertainties will not be resolved for a long time.

This study is a part of the ongoing analyses being conducted for the DOE's Nuclear Fuel Storage and Transportation Project. The purpose of this study was to provide an initial high-level evaluation of what it would take to unload all the reactor sites with account for the major uncertainties in the waste management system and using timing assumptions from the Administration's Strategy. The major questions 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 either provide specific details or suggest specific options. It was rather meant to identify the issues that might be important for planning transportation campaign in the future.

II. TRANSPORTATION SIMULATIONS

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 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 needs to arrive with 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. This includes 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) speed 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 meets 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 a consolidated 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), with and without a consolidated storage facility) were considered. These two transportation schemes are shown in a diagram 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 the SNF will be transported to a consolidated storage facility co-located with the repository starting from 2021. This scenario was intended to show the effects of an extended transportation campaign (2021 to 2098). The transportation campaign in the other scenarios is from 2048 to 2098.

The group B scenarios assume that the SNF will be transported from the reactors sites to a consolidated storage facility starting from 2021 until 2048. Starting from 2048 the SNF will be transported from the reactor sites and from the consolidated storage facility directly to a repository. All scenarios, except B5, assume that the consolidated storage facility is in south-east location. Scenario B5 considers a north-west location.

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

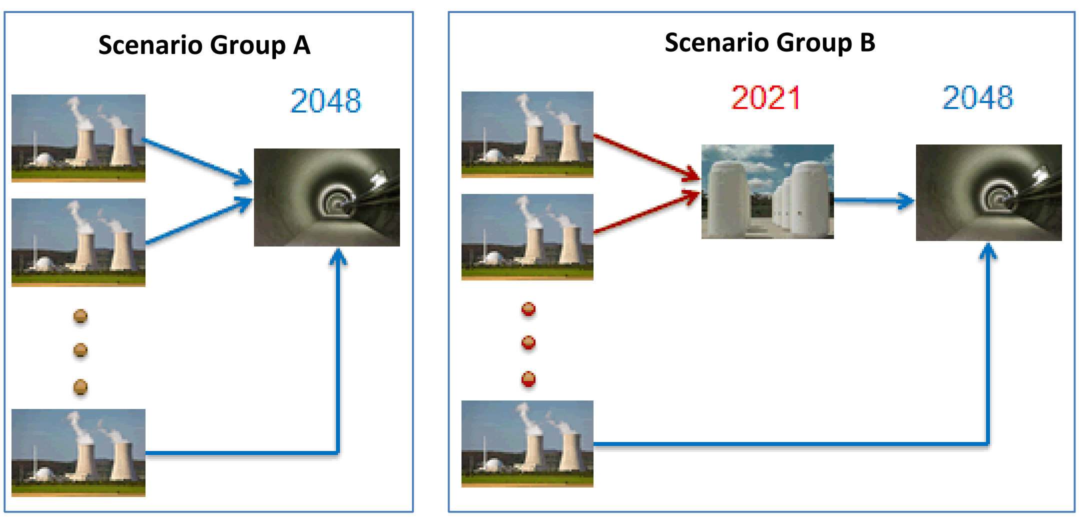


Fig.1. Two Transportation Schemes Considered in the Analysis.

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**	**CSF 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**

Two general cases of at-reactor practices were considered. In the first case, it was assumed that the existing site-specific dual purpose storage canisters (DPCs) will be loaded at reactors 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 switch to loading smaller, purpose-designed multi-purpose canisters (MPCs). The MPC definition used here is the same as that used internationally: a sealed canister intended for storage, transport, and disposal. he 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. 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 later 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 TOM database. The actual time that will be needed for these operations can be different from these values. The longer loading and unloading time may affect the transportation operations because they will lead to the longer trip durations. Same is true for the slower train speed. Scenario A1-d and B1-d considered twice longer loading and unloading times than the original ones. Scenarios A1-e and B1-e considered both, twice longer loading and unloading times and slower train speed on the mainline rail (35mph instead of 55mph).

IV. TRANSPORTATION ANALYSIS RESULTS

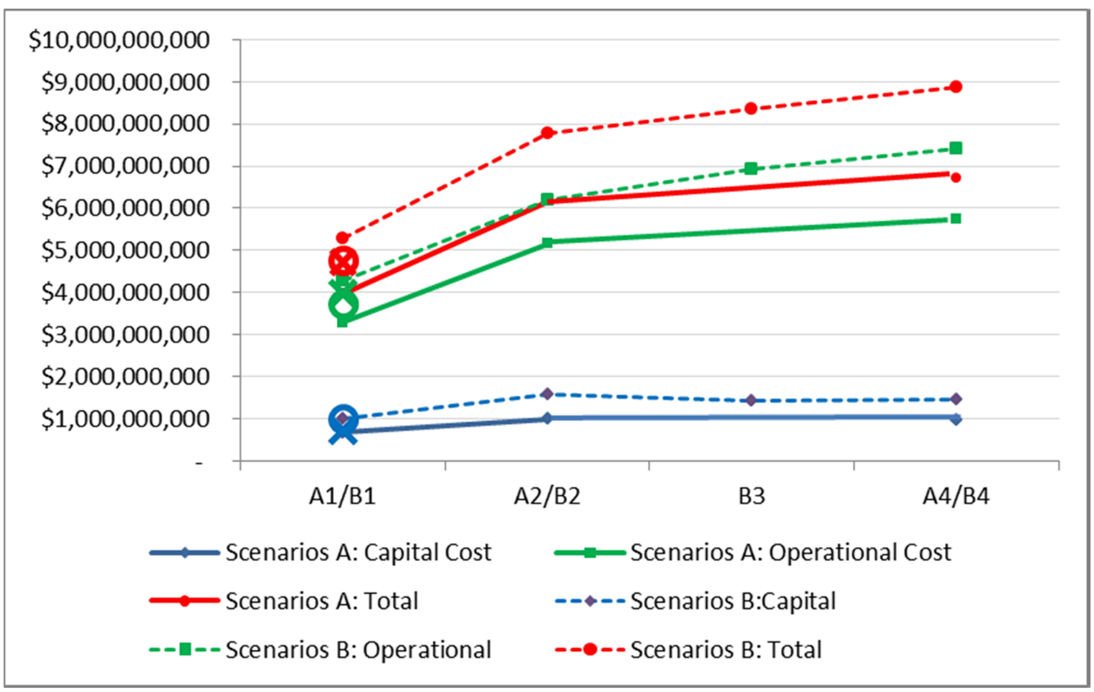
IV.A. Transportation Scheme and At-Reactor Practice

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 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 significantly smaller impact. In general, the sooner is the switch, the more MPCs are loaded and the higher is the total cost. This is true for both transportation schemes, with and without the consolidated storage facility.

Including consolidated storage facility increases the total transportation costs, but the impacts are smaller compared 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 consolidated 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 (consolidated storage located in north-west). The impacts from the extended transportation campaign (as compared to scenario A1) and different consolidated storage facility location (as compared to scenario B1) on the total cost are very small.

The capital costs in all the scenarios shown in Figure 2 are very 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. Note that about half of all the capital costs occur during the first 6 years of the campaign in the scenarios with the existing canisters (DPCs). In the scenarios with MPCs, an additional large acquisition occurs in the year of 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.

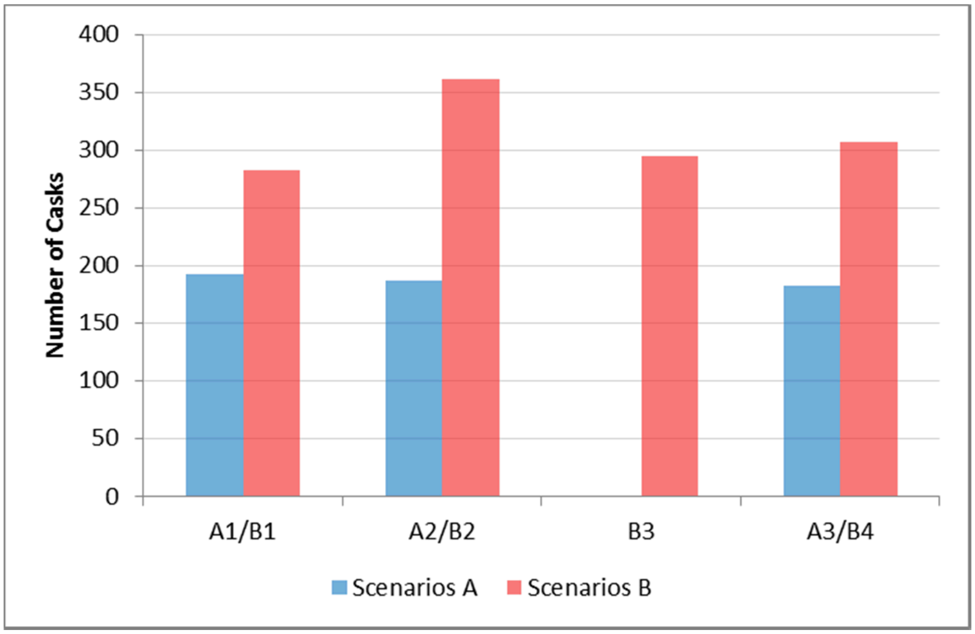


Fig. 3. Cask Acquisition for the Scenarios with Different Transportation Schemes and At-Reactor Management Practices.

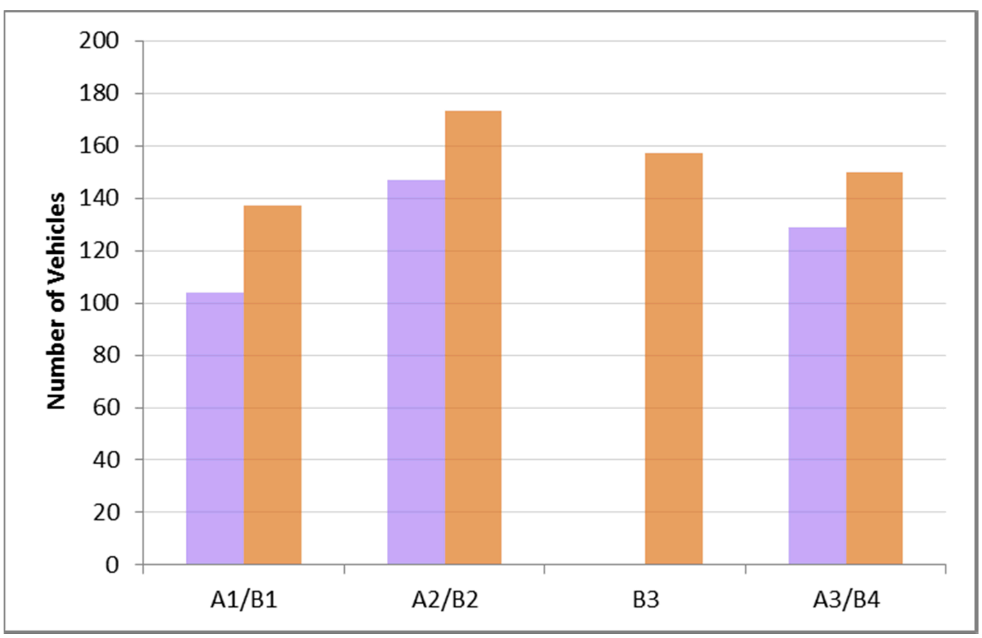


Fig. 4. Vehicle Acquisition for the Scenarios with Different Transportation Schemes and At-Reactor Management Practices.

Figures 5 and 6 show spending profiles for the scenarios with the different transportation schemes. The capital costs calculated in the scenarios without the consolidated 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 in the corresponding scenarios with and without the consolidated storage facility during 2048-2098 time period. The additional total costs in the scenarios with the consolidate storage facility are due to the costs incurred during the 2021 to 2048 time period when the transportation from the reactor sites to the consolidated storage facility takes place.

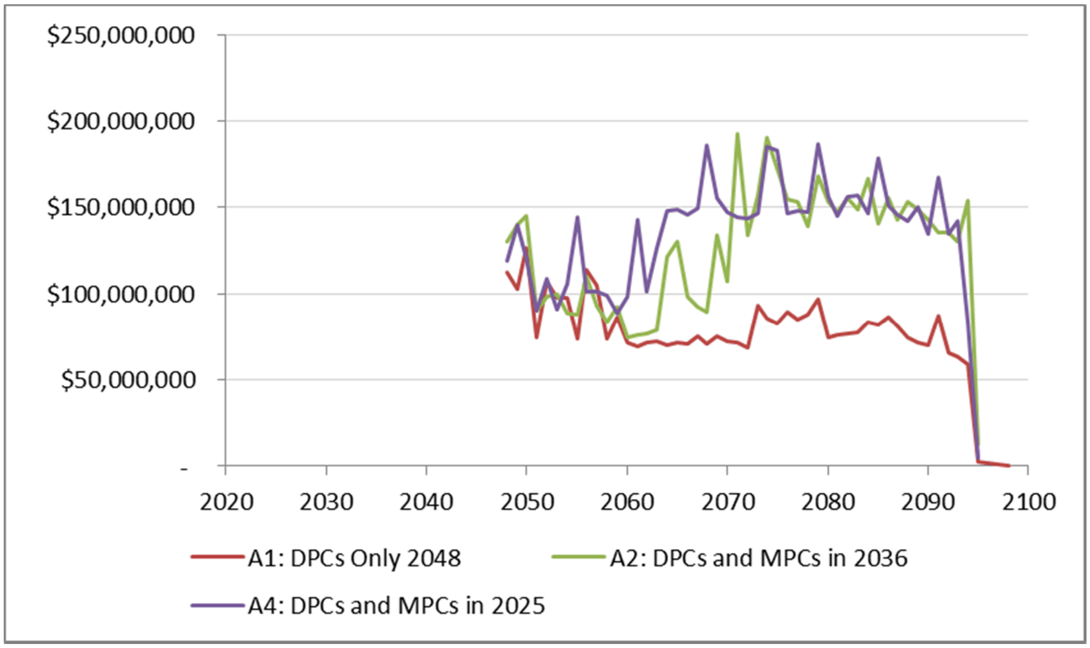


Fig. 5. Spending Profiles for the Scenarios without Consolidated Storage Facility.

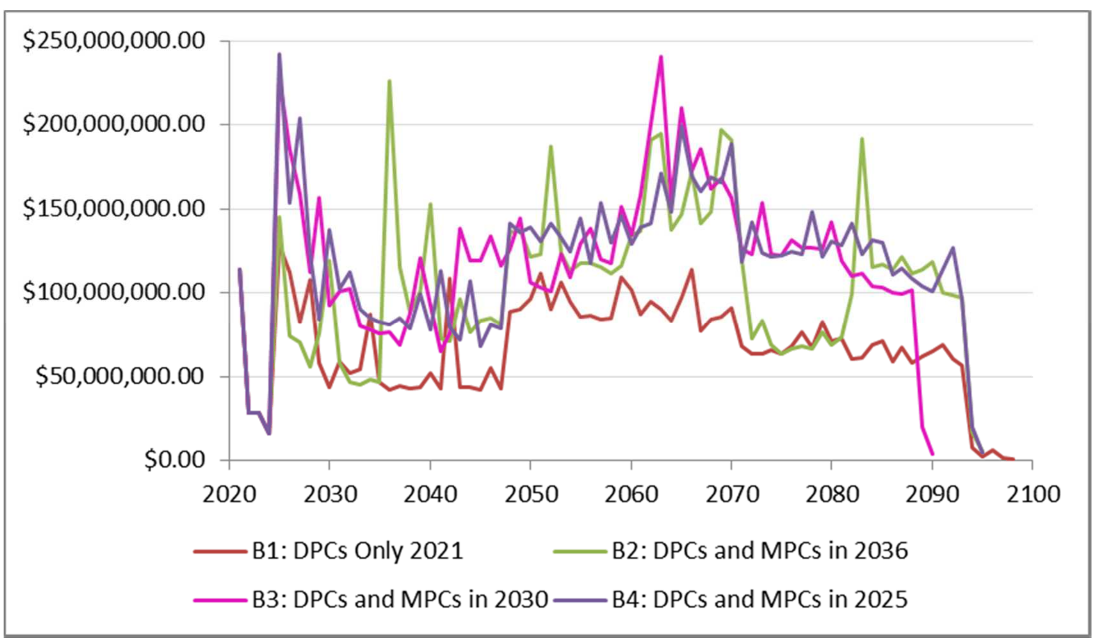


Fig. 6. Spending Profiles for the Scenarios with Consolidated Storage Facility.

IV.B. Maximum Consist Size

Using large consists may seem to be an attractive option because of the two reasons. First, fewer trips will be required to unload the reactor sites and consolidated storage facility (if applicable). This should decrease the total transportation costs that are driven by the operational costs. Second, the total distance traveled with the loaded casks should be shorter in the case of a large consist. This may reduce the number of accidents during the transportation campaign, which is calculated as the loaded cask miles (km) traveled times the accident rate (accident per railcar-km).

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

The total costs, cask miles, consist miles, and the cask miles to consist miles ratios are summarized in Table II. The cask miles are virtually the same and are equal to 56.78 million miles (scenarios without consolidation storage facility) and 98.05 million miles (scenarios with the consolidated storage facility). Consequently the number of accidents is independent of the consist size.

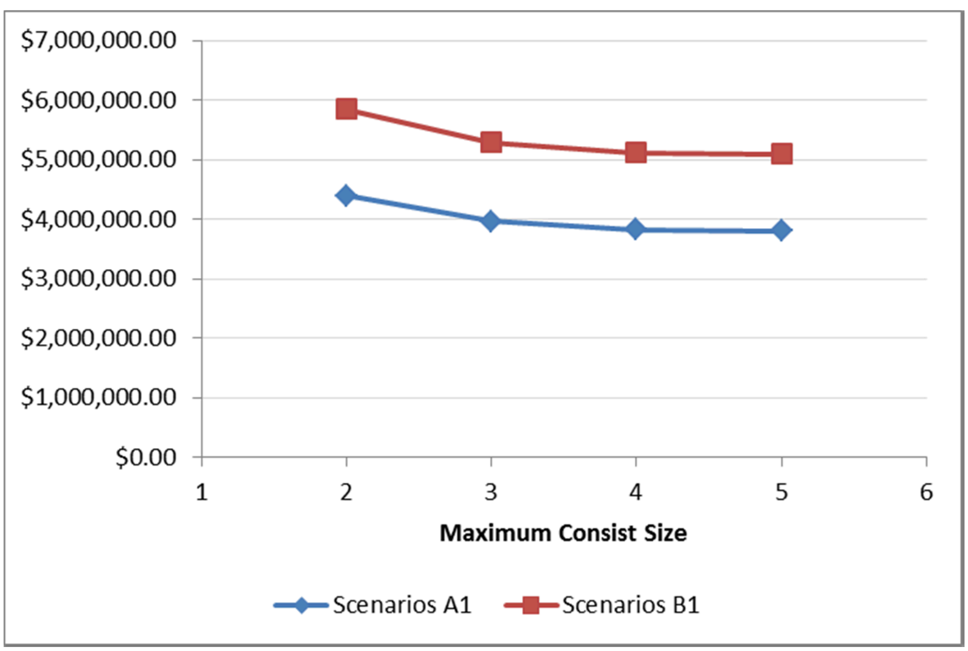


Fig. 7. Total Transportation Cost as a Function of the Maximum Consist Size.

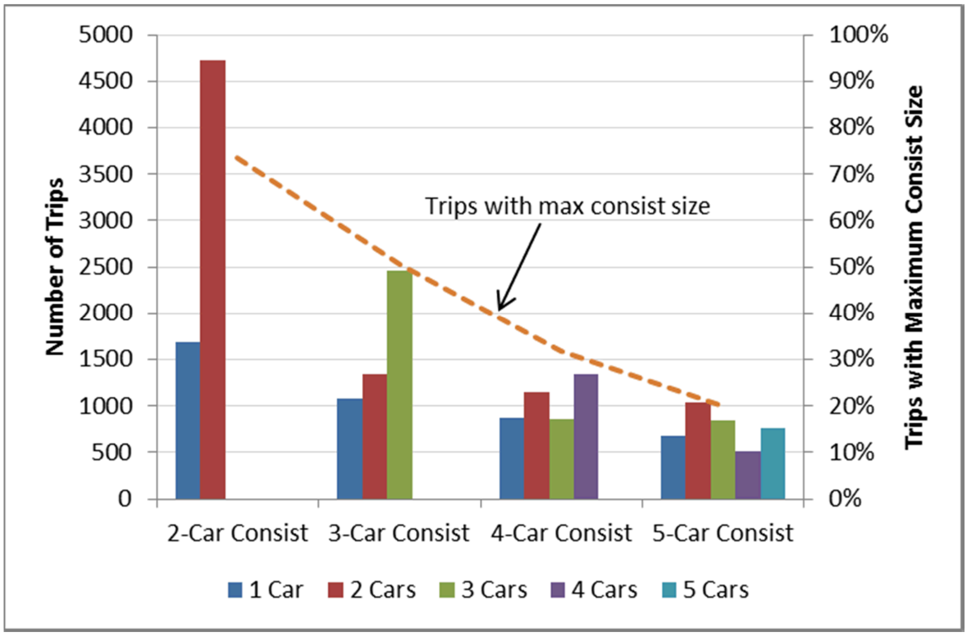


Fig. 8. Number of Trips with the Different Number of Railcars for the Scenarios without the Consolidated Storage Facility.

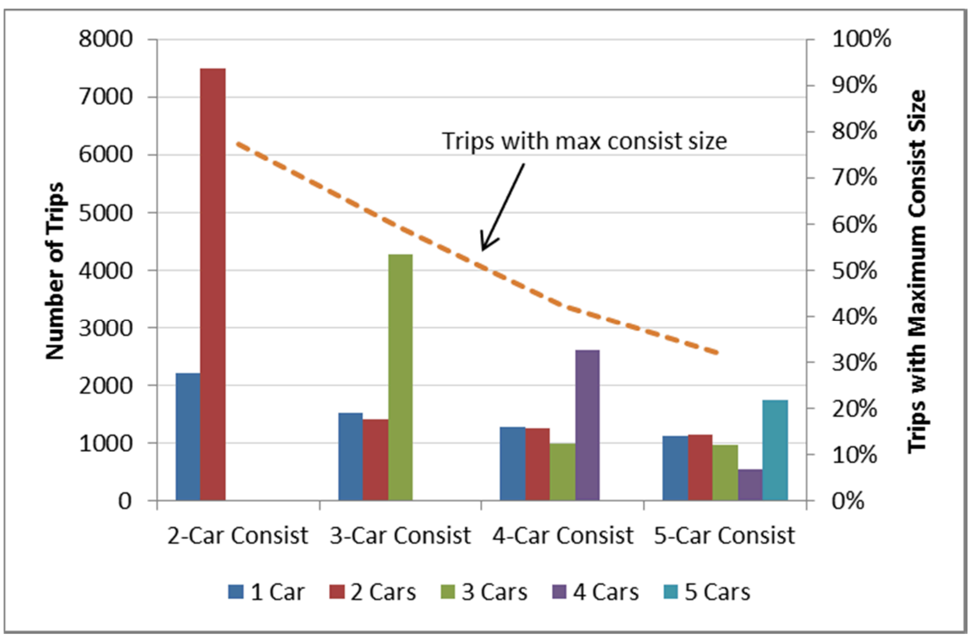


Fig. 9. Number of Trips with the Different Number of Railcars for the Scenarios with the Consolidated Storage Facility.

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

Scenario ID	Maximum Consist Size	Total Cost $B	Cask Miles	Consist Miles	Cask Miles to Consist Miles Ratio
A1-a	2	4.40	5.678E+07	3.273E+07	1.73
A1	3	3.97	5.678E+07	2.487E+07	2.28
A1-b	4	3.83	5.678E+07	2.171E+07	2.61
A1-c	5	3.80	5.678E+07	1.976E+07	2.87
B1-a	2	5.52	9.805E+07	5.526E+07	1.77
B1	3	5.29	9.805E+07	4.109E+07	2.39
B1-b	4	5.12	9.805E+07	3.484E+07	2.81
B1-c	5	5.09	9.805E+07	3.128E+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 very 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.

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. Two-fold increase in loading and unloading times result in 1% to 3 % increase in the total transportation costs.

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

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 a consolidated storage facility). The scenarios in these figures are the ones in which only DPCs are loaded at the reactor sites.

In the scenario without a consolidated storage facility the SNF age during the transportation gradually changes from 66 year old at the beginning of the campaign to 45 year old at the end of campaign. By 2048 about 85% of SNF at the reactor sites is in the dry storage canisters. As the result, the SNF loaded for transportation mostly comes from the dry storage. This explains 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.

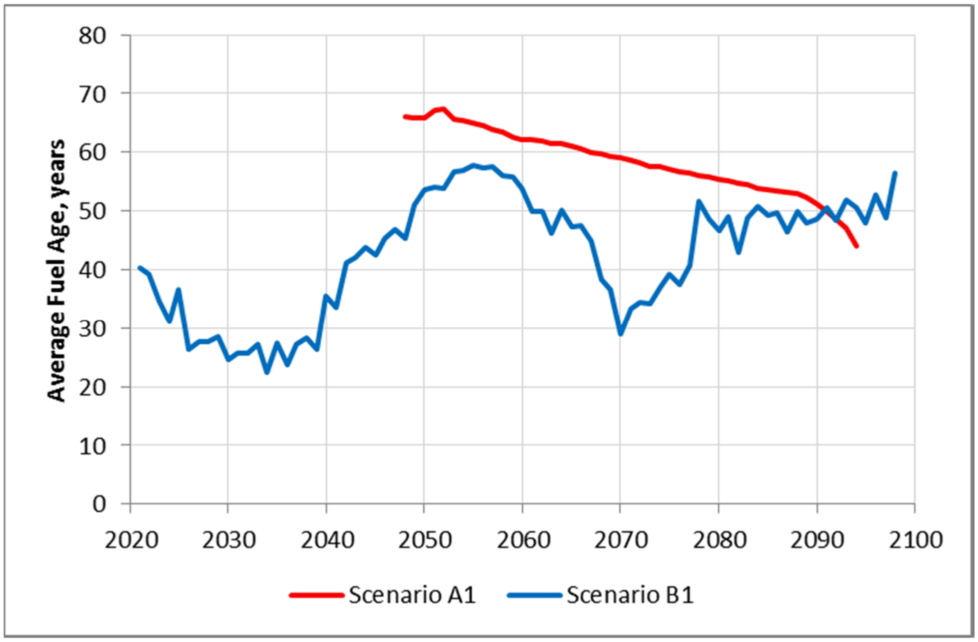


Fig. 10. Average SNF Age during the Transportation.

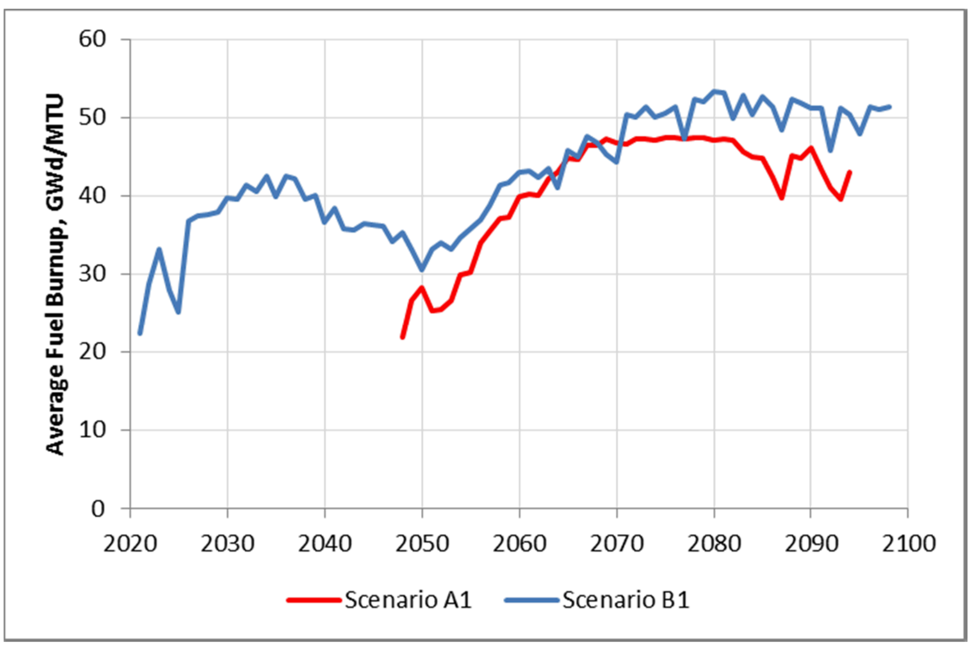


Fig. 11. Average SNF Burnup during the Transportation.

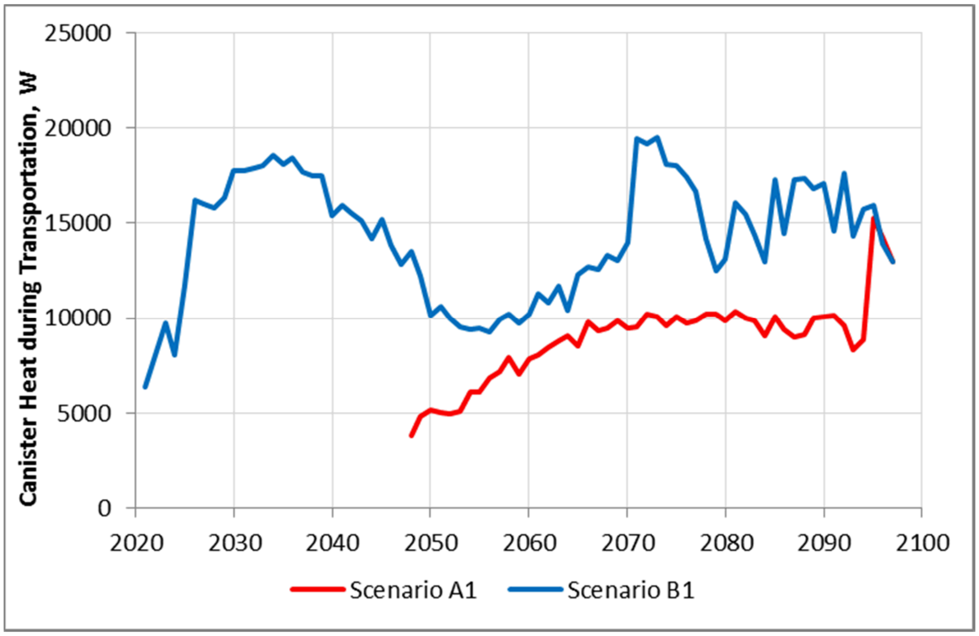


Fig. 12. Average Canister Heat Output during the Transportation.

In the scenario with the consolidated storage facility the age, burnup, and canister heat output profiles are more complex. The fuel age is 20 to 40 year old during the first 20 years of campaign and is around 50 year 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 reactors site. Only 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 consolidated storage facility.

V. CONCLUSIONS

A large-scale transportation campaign spread over at least a few decades will be required to unload the reactor sites. The design of such 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 campaign in the future. The major findings of the 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 with the consolidated storage facility. In the scenario considered, the impacts on the total cost from using the small canisters were greater than the impacts from including the consolidated storage facility. The ROM total transportation cost ranged from $4B to $9B.

An acquisition required to conduct the transportation campaign and the corresponding capital costs are less affected by the scenario parameters. In the scenario 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 were from $0.7B to $1.6B.

The differences in the spending profiles mainly reflect the differences in the operational costs. In the scenario 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 allocated between a few years prior to the year in which the acquisition is actually needed.

The factors such as the location of a consolidated 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 using larger consists does not reduce the cask miles and thus, the number of accidents per campaign. This is because the pickup schedule is very 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. The scenarios with 3 car consist considered in the analysis required 50% - 60% of the trips with the 3 car consist, 20% - 27% of the trips with the 2 car consist, and 21% - 22% of the trips with the 1 car consist.

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

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