INITIAL EVALUATION OF STANDARDIZED CANISTERS IN THE WASTE MANAGEMENT SYSTEM*

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Development and deployment of a standardized canister system represents an opportunity to develop an integrated approach to address storage, transportation, and disposal issues in the waste management system. However, this deployment has the potential for significant system-wide impacts regardless of timing and method of deployment. This evaluation compares continued loading of dual-purpose canisters (i.e., status quo) with loading of standardized canister systems in the near-term, before repository requirements are known and/or before operating reactors shut down. This evaluation quantitatively compares order of magnitude costs and logistics for different standardization scenarios with status quo scenarios, provides insight into quantifiable impacts of loading standardized canister systems in the near term, tests system-level analysis tools and associated input, and identifies scenarios for further analysis.

Data used for at-reactor and repackaging operations must be updated to provide more realism at the system level. Based on the assumption that the cost to load any canister regardless of capacity was the same, loading the smallest (four pressurized water reactor [PWR] assemblies) canisters at reactors was the most expensive, most challenging option. Total system costs of loading either the medium (twelve PWR assemblies) or the large (twenty-one PWR assemblies) standardized canister systems before the waste-package capacity is determined are similar to the continued loading of current DPCs, though where those costs occur does change.

I. INTRODUCTION

The Nuclear Fuels Storage and Transportation Planning Project (NFST) of the US Department of Energy (DOE) Office of Nuclear Energy (NE) has initiated a quantitative assessment of waste management system strategies. The assessment includes the current status quo approach of using large dual-purpose canisters (DPCs) optimized for each utility's near-term storage needs, along with alternatives such as adopting standardized spent nuclear fuel (SNF) canister systems that are designed with storage, transportation, and final disposal being considered. This paper documents the first step in this assessment, which focuses on incorporating standardized canister systems into the waste management system at reactors before the disposal requirements are known. Specifically, this assessment assumes that those disposal requirements would result in a maximum number of assemblies that could be disposed in a waste package (WP) (i.e., WP capacity). It is assumed that if the capacity of a standardized canister is compatible with the repository, then the canister would be placed in a WP overpack at the repository in preparation for disposition (i.e., WP-compatible canister).

I.A. Background

Nuclear utilities make site-specific decisions on how to manage their SNF. For dry storage, most utilities use high-capacity canisters able to hold 32 pressurized water reactor (PWR) assemblies or 68 boiling water reactor (BWR) assemblies, and some utilities are beginning to use the latest ultra-high-capacity canisters that are able to hold 37 PWR or 87/89 BWR assemblies. Even though most utilities use DPC systems that could also be used to transport SNF off site, on-site, dry storage remains the focus because there is no defined destination to which the DPCs could be transported. In addition to transportability requirements, any canisters that will be disposed of will need to meet repository constraints. Unless this disposal feasibility is determined and demonstrated in a repository licensing process, the SNF in the current DPCs will have to be repackaged into smaller canisters specifically designed to be disposable per future repository requirements.

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I.B. Motivation

To minimize the potential for repackaging, increase flexibility in the waste management system, simplify waste management operations, and minimize uncertainties of waste management system performance, standardized multi-purpose (storage, transportation, and disposal) canister systems have been considered for many years.[1,2] However, there are two outstanding issues related to standardized canisters: (1) absent repository selection, there are no site-specific disposal requirements for a WP, and (2) any change in canister design has the potential to impact utility operations if newly designed canisters are loaded at operating reactor sites.

Based on initial assumptions, these two issues are quantified. Specifically, the potential at-reactor and total system impacts of loading standardized canisters before the WP capacity is known are quantified. A determination on whether or not and how to go about incorporating standardization into the integrated waste management system requires a strong, defendable basis; this evaluation provides the first step in this basis.

II. SCENARIOS AND ASSUMPTIONS

In this evaluation, the following terms have specific meanings. A "strategy" is a relatively near-term (within the next 10–15 years) policy decision on whether to implement a specific plan for standardized canister systems (e.g., begin loading smaller standardized canister systems at reactor sites). A "response to outcome" is a course of action to be taken after a particular outcome becomes known, such as the definition of disposal requirements following a determination of the repository characteristics. A "scenario" includes the strategy and the response to the outcome, and it includes assumptions on how both of these would be implemented.

This initial evaluation considers two strategies: (1) a status quo strategy that continues use of DPC systems and (2) a standardized canister strategy, which loads standardized canister systems of an assumed capacity at operating reactors. In all standardized canister strategies, once the WP capacity becomes known (as a result of the repository requirements), the WP-compatible canister system is then loaded.

II.A. Status Quo Strategy

The current utility-planning status quo strategy will be used as a basis for comparison with standardization alternatives. This strategy is characterized by a continued trend toward loading SNF with higher burnups, larger/higher heat-load DPCs, higher capacity canisters, and no federal action to promote any standardization. The status quo strategy involves continuing use of DPCs for at-reactor storage.

II.B. Standardized Canister Strategies

Standardized canister strategies include the following options: (1) a choice of a standardized canister system, (2) a choice of location for standardized canister loading, and (3) a choice of when the standardized canister is loaded. This evaluation focuses on strategies involving early adoption of a single standardized canister system at reactor sites.

The options for canister capacity analyzed in this evaluation are detailed in Table I. Smaller canisters are assumed to be loaded individually at reactor sites, but may be able to be stored and transported in multi-canister overpacks.

TABLE I. Standardized Canister Sizes and Overpack Capacity

Canister Size	Storage Capacity	Transportation Capacity
4 PWR / 9 BWR	4 Canisters	4 Canisters
12 PWR / 32 BWR	3 Canisters	1 Canister
21 PWR / 44 BWR	1 Canister	1 Canister
DPC[a]	1 Canister	1 Canister
37 PWR / 89 BWR	1 Canister	1 Canister

II.C. Assumptions

Most strategies assume that once repository characteristics are known, the corresponding WP requirements are defined and compatible standardized canister systems are available, SNF being unloaded from reactor spent fuel pools will be placed into WP-compatible standardized canister systems as illustrated Fig. 1. While this figure does not show all options of a given scenario, it illustrates the high-level, near-term strategies evaluated in this initial evaluation. The red arrows show only shifts in policy (e.g., moving from loading DPCs to loading standardized canister systems), but not actual repackaging operations of single

[a] DPCs include 24 PWR, 32 PWR, or 37 PWR capacity canisters. Each reactor site has selected the DPC that best suits their individual needs.

* Notice: 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.

assemblies. The need to repackage is indicated by the yellow star. Once the WP capacity is determined, only those loaded canisters that are larger than the WP capacity will be repackaged. For example, if 4 PWR canisters are loaded between 2025 and 2036 and in 2036 the WP capacity is determined to be 12 PWR, then those 4 PWR canisters would not be repackaged. Instead they would be disposed in either individual WPs or in a multi-canister WP. It is also assumed that legacy canistered SNF will be repackaged into such standardized canister systems at the repository if needed. To clarify, only the direct disposal of all existing DPCs results in no repackaging. Even if standardized canister systems were implemented by 2025 and were compatible with eventual disposal, the existing DPCs (~3,500 by 2025) will need to be repackaged unless it can be shown that they would be disposable in a specific site/repository design combination.

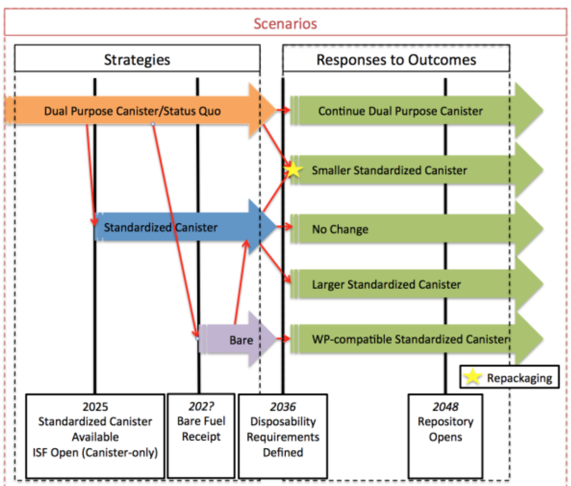

Fig. 1. Three main system strategies and potential responses to outcome (Bare fuel is not analyzed in this evaluation).

Other assumptions used for all scenarios are as follows:

- the at-reactor cost to load any canister regardless of capacity is the same
- all canister systems can be produced at the required rate
- the reference fuel inventory projections include 60 year operating lifetimes for all currently operating reactors
- the system acceptance rate is 3,000 metric tons of heavy metal per year, the allocation strategy is oldest-fuel-first which is consistent with the Standard Contract, and the acceptance strategy is youngest-fuel-first after 5 years

related to near-term implementation of standardized canister systems.

- if an interim storage facility (ISF) is included in the scenario, all fuel is transported to the ISF until the repository opens.

If an ISF is included in the scenario, the following assumptions were made:

- no packaging or repackaging activities occur at the ISF
- all canisters will be stored in overpacks consistent with the sizes described in Table 1, and
- there is no capacity limit at the ISF.

The following repository assumptions were made:

- there is no capacity limit for storage before canister emplacement,
- all packaging and repackaging operations occur at the repository facility,
- if the 37 PWR standardized canister system is assumed to be disposable, all legacy DPCs are also assumed to be disposable, and
- there are no repository capacity limits for final disposition.

The nominal schedule assumptions are:

- the ISF accepts DPCs from shutdown reactors in 2021,
- reactors begin loading standardized canister systems in 2025,
- the ISF begins accepting DPCs and/or standardized canister systems at 3000 metric tons of heavy metal per year (MTHM/year) in 2025,
- the repository is sited in 2026,
- the WP capacity is known with high confidence in 2036, and
- the repository is fully operational in 2048.

These dates are varied in some scenarios.

III. DETAILED SCENARIO DESCRIPTIONS

Scenarios consist of an initial strategy (i.e., size of canister to load), an outcome (i.e., WP size), and a response to outcome (i.e., immediately switch to waste-package-compatible canister). Scenarios include assumptions on when and where they would be implemented. Scenarios encompass the entire time period of the system, including initial/boundary conditions (system start to finish) for an assumed outcome and the response to that outcome. Fifty-two scenarios were analyzed to (1) identify areas for more refined future study, (2) identify areas where input information could be improved/confirmed, and (3) gain insight into impacts

III.A. Status Quo Class

All scenarios in the status quo class include the status quo strategy, which continues use of DPC systems with no actions taken to increase the likelihood that DPCs can be used for storage, transportation, and disposal. There are 14 scenarios in the status quo class. This class was established to provide a baseline for comparison to scenarios where standardized canister systems were introduced early in the waste management system. This status quo strategy is consistent with the utilities' current loading decisions (i.e., load large DPCs). These scenarios include the following assumptions: (1) WP size (4 PWR, 12 PWR, 21 PWR, DPCs), (2) if an ISF is included in the system, and (3) if the reactor is switching to loading standardized canisters when the WP is known.

III.B. Standardized Canister Class

All scenarios in the standardized canister class implement the standardized canister strategy. This implies that all reactors begin loading a standardized canister system before the disposal requirements are known (either 2025 or 2030 in all scenarios). This class was established to provide variations on the different standardized canister system options. These scenarios include implementation of a specific-capacity standardized canister system early in the waste management system. There are 40 scenarios in the standardized canister class. All scenarios assume that (1) an initial standardized canister is selected in 2025 or 2030 before the WP is known in 2030, 2036, or 2040, and (2) once the WP is known, all reactors will switch to loading WP-compatible, standardized canisters. These scenarios include the following assumptions: (1) WP size (4 PWR, 12 PWR, 21 PWR, 37 PWR), (2) if an ISF is included in the system, (3) the date the reactor begins loading standardized canisters (2025 or 2030), (4) the date the WP size is known (2030, 2036, 2040), and (5) the date an ISF is fully operational (2025, 2030).

IV. RESULTS AND OBSERVATIONS

One goal for this initial evaluation was to understand results in the context of the system computational model inputs, boundary conditions, and assumptions. Another goal was to begin to understand the system-wide impacts of incorporating standardized canisters before the WP is known. All scenarios were analyzed with the TSL-CALVIN (Ref. 3) analysis tool. Due to the large amount of information, the results and analyses have been summarized at a high level in the system results section and then broken down into four sub-sections: (1) at-reactor, (2) transportation, (3) ISF, and (4) repackaging. As mentioned above, the assumption that loading any canister regardless of capacity had the same cost was used due to lack of experience and information loading smaller canisters at reactors. This assumption has a strong correlation to at-reactor costs and will be confirmed or updated in future work.

IV.A. System Results

Strategies with smaller canisters require that more canisters be used in the system. This results in logistical and operational challenges, including (1) increased at-reactor loading operations, (2) a higher use of transportation infrastructure, (3) greater capacity ISF facilities to receive, store, and ship SNF, and (4) larger capacity repackaging receipt facilities. However, smaller canisters may provide benefits by reducing the number of canisters requiring repackaging prior to disposal.

The total system cost information shows how management strategies and responses to outcomes affect relative costs. Use of these rough order of magnitude (ROM) cost results for other purposes should be avoided for several reasons:

- simplified assumptions are used in this evaluation when describing the alternative SNF management strategies,
- significant portions of the input data assumptions related to standardized canisters (e.g., at-reactor costs, ISF design concepts) are based on limited or no operational or design experience,
- key factors such as waste management system costs for siting, characterization, and licensing for repository facilities are not included, and
- costs associated with delay in the waste management program, which are potentially greater for some concepts than others, are not included.

All metrics are tabulated from 2020 forward.

The percentage change in total system cost is shown in Figure 2 for scenarios with a final WP size of 4 PWR.

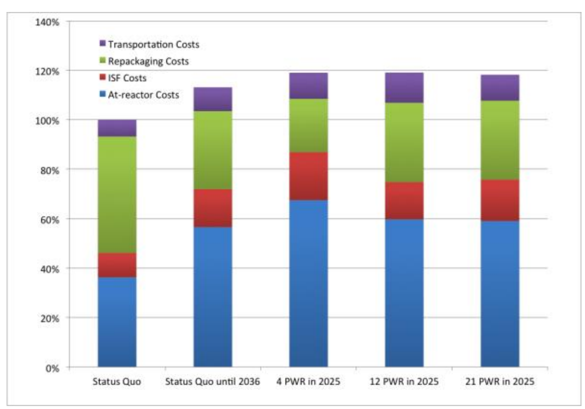

Fig. 2. Total system ROM costs when the WP is a 4 PWR canister.

The base case is the status quo scenario where standardization is not introduced at reactors. As Figure 2 illustrates, based on current at-reactor loading procedures and cost assumptions, it would be more economical to continue loading DPCs at reactors and then repackage all DPCs at a dedicated repackaging facility rather than loading 4 PWR canisters at reactors one at a time using current canister loading procedures.

Figures 3, 4, and 5 show the total system costs when the 12 PWR canister, the 21 PWR canister, and the DPC are determined to be the WP. These figures show that there are relatively small total system cost differences between different strategies, which can be attributed to the fact that all standardization scenarios change to the correct WP size in 2036. The SNF loaded after 2036 impacts the results more than the SNF loaded between 2025–2036.

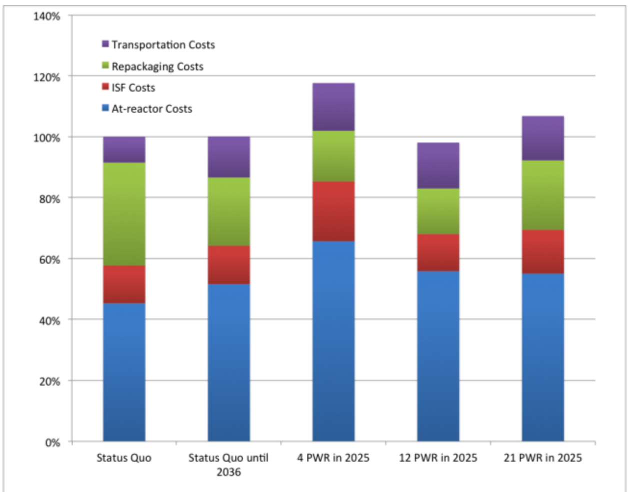

Fig. 3. Total system ROM costs when the WP is a 12 PWR canister.

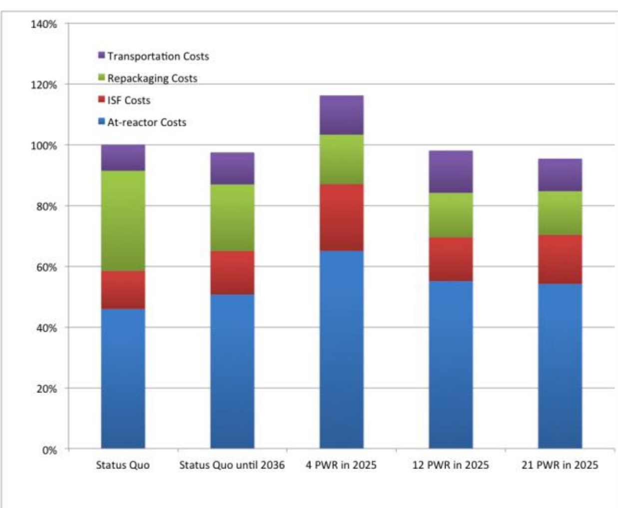

Fig. 4. Total system ROM costs when the WP is a 21 PWR canister.

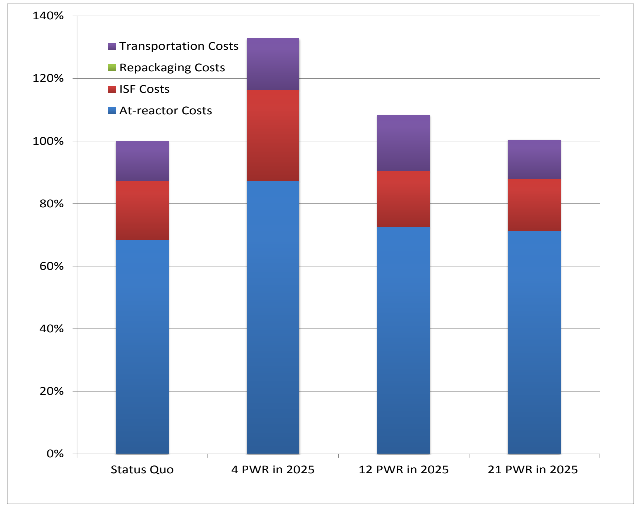

Fig. 5. Total system ROM costs when all canisters, including DPCs, are disposable.

The 21 PWR canister scenarios have lower ROM costs than those in the status quo scenario in Figure 5 because the standardization scenarios switch to a 37 PWR canister in 2036 at all reactors, whereas the status quo scenario continues the currently loaded DPCs (which in many locations are smaller than 37 PWR).

IV.B. At-Reactor Results

When comparing different scenarios, the potential to load a large number of canisters at reactors is shown in Table II. These scenarios are those that result in the maximum number of canisters being loaded at reactors once the use of standardized canisters begins in 2025. The maximum number of canisters loaded at any operating reactor in a given year for these scenarios is shown in Figure 6.

TABLE II. Total Number of Canisters Loaded at All Reactors

Canister Size	Number of Canisters Loaded at Reactors
4 PWR	58,141
12 PWR	18,994
21 PWR	12,264
DPC	8,882

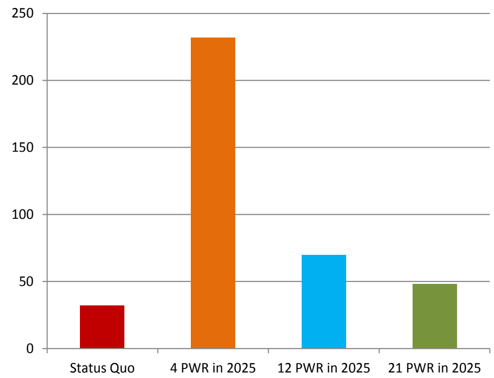

Fig. 6. Maximum number of canisters loaded at any operating reactor in a given year as a function of WP size.

These logistical results show that those strategies where 4 PWR canisters are loaded at reactors are operationally challenging due to the large number of canisters that must be loaded.

The total number of years all reactors are shutdown and have SNF onsite are shown in Table III, which illustrates that the date an ISF begins operation is much more important to the ability to get fuel off of reactor sites than the standardization strategy.

TABLE III. Maximum and Minimum Number of Shutdown Reactor Years for All Reactors

ISF Start Date	Shutdown Reactor Years	
	Min	Max
2025	2,035	2,177
2030	2,410	2,410
Never	3,868	3,907

IV.C. Transportation Results

The transportation results show that the largest number of loaded overpack miles is traversed in the 12 PWR canister system. This is because this scenario has the fewest assemblies per rail car (12 PWR per car) versus the 4 PWR scenarios in a multi-canister overpack (16 PWR per car) or larger canisters. The status quo scenario is considered the base case, and the other scenarios are compared as a percentage against the base case, as shown in Figure 7.

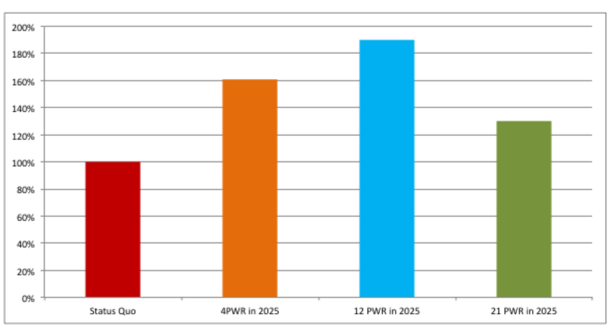

Fig. 7. Percentage of loaded overpack miles as a function of canister loading strategy assuming that the specific canister strategy was loaded indefinitely after 2025.

IV.D. Interim Storage Facility Results

The ISF results show that the smaller canister scenarios have more canisters stored at the ISF as well as have more bays for shipping and receiving canisters. If the final WP capacity is determined to be a 21 PWR canister, Figure 8 shows that the maximum number of loaded overpacks at the ISF ranges from just over 5800 loaded overpacks for the status quo case with no standardized canisters to more than 8600 loaded overpacks for the case where 4 PWR canisters were loaded between 2025 and 2036.

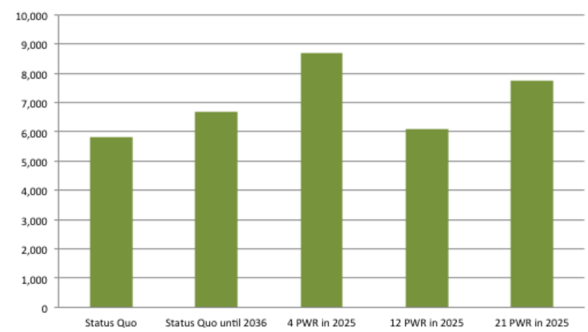

Fig. 8. Maximum number of loaded overpacks at the ISF in any year as function of standardization strategy when 4 PWR canisters are determined to be the WP.

The number of ISF receipt and shipping bays goes up fairly proportionally with the total number of canisters accepted annually. This ensures that the 3000 MTHM/year throughput is achievable when there is less SNF in each canister. Therefore, the scenarios that load 4 PWR canisters at any time at the reactor sites require significantly more receipt and shipping bays. In all scenarios where 4 PWR canisters are loaded at any point (2025–2036 or 2036 onward), the number of receiving bays ranges from 22 to 28. As evident in Table IV, this is significantly more than the 12 PWR cases (excluding smaller canisters) with 10 bays, the 21 PWR cases with 4 to 6 bays, and DPC/37 PWR cases with 4 bays.

TABLE IV. Number of Receipt and Shipping Bays at an ISF as a Function of Scenario for Smallest Canister Size

Smallest Canister Size	Minimum	Maximum
4 PWR	22	28
12 PWR	10	10
21 PWR	4	6
DPC/ 37 PWR	4	4

IV.E. Repackaging Facility Results

The repackaging facility results are similar to the ISF results. An increased amount of canisters in the system requires larger receipt facilities and larger bays for repackaging (opening and closing). The number of opening and closing bays as a function of canister size can be seen In Tables V and VI.

TABLE V. Number of Opening Bays as Function of Canister Loading Strategy

Initial Canister Loading Strategy	Number of Opening Bays
DPC	3
21 PWR	3–4
12 PWR	3–6
4 PWR	3

TABLE VI. Number of Closing Bays as a Function of WP Size

WP Size	Number of Closing Bays
37 PWR / DPC	0
21 PWR	4–5
12 PWR	6–7
4 PWR	18–22

As expected, the number of opening bays is driven by the initial standardization strategy, whereas the number of closing bays is driven by the final WP size. The large number of closing bays is driven more by the legacy DPCs than the standardization strategy and the number of closing bays is scenario dependent based on which canisters are accepted during which years.

The volume of low-level waste (LLW) generated by canisters that cannot be used for final disposition ranges from 0 (all DPCs are disposable) to more than 125,000 m^3 in the case where all DPCs must be repackaged. Figure 9 shows the LLW volume from different scenarios if the WP is determined to be a 4 PWR WP.

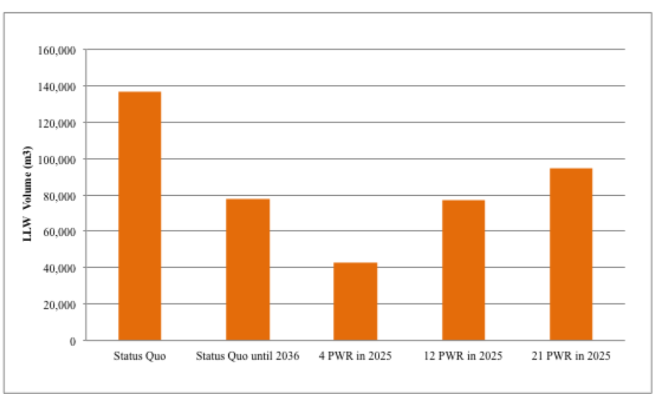

Fig. 9. Cubic meters of LLW when the WP size is determined to be a 4 PWR canister.

Note that by 2025 there will be slightly more than 40,000 m^3 of LLW from DPCs to be repackaged in many of the scenarios considered.

V. CONCLUSIONS

This paper documents the initial evaluation of incorporating standardized canister systems at reactors before the WP is known and compares these scenarios with continual loading of large DPCs at reactors. Because this is an initial evaluation, all observations should be considered preliminary. However, there are a few over-arching takeaways from this work.

Loading 4 PWR canisters at reactors using the current methods has significant cost and operational impacts at all facilities in the waste management system, based on the assumption that the cost to load any canister is the same regardless of canister capacity. As a result of this observation, DOE has initiated two separate work activities to better define a 4 PWR canister system and to determine if there are more effective loading operations that would minimize these impacts and provide a basis for different assumptions related to at-reactor loading.

Furthermore, the overall system is driven more by the legacy DPCs (past–2025) and the WP compatible system (2036–onward) than the canisters loaded between 2025 and 2036. Initial results indicate that while there are tradeoffs in which costs and operations are more significantly impacted, the total system costs and operations are fairly unaffected by loading 12 PWR, 21 PWR, or DPCs between 2025 and 2036.

In the future, additional scenarios that include bare fuel transportation to an ISF will be incorporated, along with the potential impacts of handling smaller-than-required canisters at the repository. Work activities related to understanding at-reactor operational impacts and the 4 PWR canister system will provide better data related to loading times and costs for use in refining this preliminary analysis.

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