Logistics Modeling of Emplacement Rate and Duration of Operations for Generic Geologic Repository Concepts – 16529

(SAND2015-9947 C)

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ABSTRACT

This study (1) identifies 16 potential geologic repository concepts for disposal of commercial spent nuclear fuel (SNF) and (2) evaluates the achievable repository waste emplacement rate and time needed to complete disposal for these concepts. Total repository capacity is assumed to be 140,000 MTU of spent fuel. The results provide important input to rough-order-of-magnitude (ROM) cost estimates for SNF disposal alternatives.

The disposal concepts cover three categories of host geologic media: crystalline, salt, and argillaceous rock. Four waste package sizes are considered: 4PWR/9BWR; 12PWR/21BWR; 21PWR/44BWR, and dual purpose canisters (DPCs) packaged for disposal. Each concept is associated with package thermal power limits for emplacement and repository closure (the same for some concepts).

To estimate the repository emplacement rate and duration of operations, logistical simulations were performed using assumptions on interim SNF storage, disposition of SNF stored in DPCs, repository opening date, and throughput rates for storage and disposal facilities.

The simulations demonstrate that all concepts and scenarios, with few exceptions, are similar with regard to achievable emplacement rate and duration of operations. Throughput of 3,000 MTU per year can be maintained during the first 44 years of repository operations. Most of the inventory (99%) can be emplaced within 54 years of repository operations (the remaining 1% could require additional aging or smaller packages).

Estimating ROM disposal cost was not an objective of this analysis, however, an example of disposal cost is provided to demonstrate key differences between concepts.

INTRODUCTION

The cost of a geologic repository is a significant part of the radioactive waste management system. The disposal cost will depend on the type of geologic media, waste package size, waste emplacement rates, and many other factors. This study provides an important input for the rough-order-of-magnitude (ROM) disposal cost analysis.

First, sixteen potential geologic repository concepts for disposal of spent nuclear fuel (SNF) were identified [1]. Published international experience (for example, Refs 2 through 5) was used to develop these concepts, where applicable. The disposal concepts cover three major categories of host geologic media; four waste package sizes; and 6 emplacement power limits for either emplacement or repository closure (Table I).

TABLE I. Summary of Potential Geologic Repository Concepts

Geologic Medium	Waste Package Capacity	Concept ID	Emplacement Thermal Power Limit (kW)	Repository Closure Thermal Power Limit (kW)
Crystalline (enclosed)	4PWR/9BWR	1	1.7	*
Argillaceous (enclosed)	4PWR/9BWR	2	1.7	*
	12PWR/21BWR	3	1.7	*
Salt (enclosed)	4PWR/9BWR	4	2.2	*
	12PWR/21BWR	5	5.5	*
	21PWR/44BWR	6	10.0	*
	DPC	7	11.5	*
Hard rock unsaturated (open)	12PWR/21BWR	8	10.0	4
	21PWR/44BWR	9	18.0	7
	DPC	10	18.0	7
Hard rock saturated (open)	12PWR/21BWR	11	10.0	2
	21PWR/44BWR	12	18.0	3
	DPC	13	18.0	3
Argillaceous (open)	12PWR/21BWR	14	10.0	3
	21PWR/44BWR	15	18.0	3
	DPC	16	18.0	3
* These concepts are backfilled at emplacement.				

For the DPC direct-disposal concepts we assumed that the existing DPCs would be sealed into disposal overpacks for direct disposal (i.e., with no extra provision for postclosure criticality control; see Ref. 6).

Enclosed emplacement modes have engineered or natural backfill/buffer material placed in contact with the waste packages at emplacement. Enclosed modes are associated with a waste package thermal power limit at the time of emplacement in the repository. The alternative open modes have packages initially surrounded by air space, ventilated to remove heat, then eventually closed possibly with the addition of backfill throughout the repository. Open modes require separate thermal power limits for emplacement and for repository closure (when ventilation stops, and backfill may be installed). For disposal concepts considered here the host geologic medium would be water saturated, except for Concepts 8, 9, and 10 which would be implemented in unsaturated, hard rock.

Next, the achievable repository waste emplacement rate and the time required to complete the disposal for the identified disposal concepts were evaluated based on logistical simulations. Total repository capacity was assumed to be approximately 140,000 MTU of spent fuel.

Note that the logistical simulations account for the emplacement power limit and the waste package size only (thermal power limits at closure were considered separately). As a result, 16 different disposal concepts could be simulated with nine scenarios. For example, Concept 1(crystalline enclosed) and Concept 2 (argillaceous enclosed) can be grouped because they have same emplacement power limit (1.7 kW) and the same waste package size (4PWR/9/BWR).

APPROACH

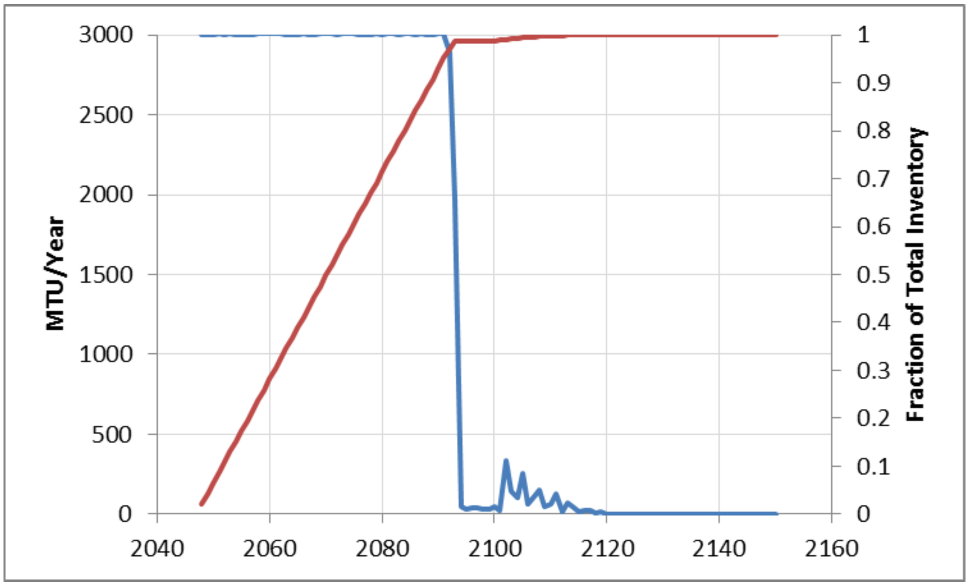
The logistical simulation code TSL-CALVIN [7] was used to simulate the SNF management system including waste emplacement. The model was set up to assume the following conditions:

- SNF is loaded into DPCs of the size now in use at operating reactor sites to keep pool inventory at or below maximum capacity.
- SNF from pools is loaded into DPCs of the size now in use starting 5 years after reactor shutdown.
- An interim storage facility (ISF) for commercial SNF becomes operational in 2021 and accepts waste from the reactor sites at the rate of 3,000 MTU per year.
- DPCs that meet the associated transportation power limits are transported from reactor sites to the ISF until all the reactor sites are unloaded.
- DPCs are stored at the ISF until the repository begins accepting waste in 2048 at the rate of 3,000 MTU per year.
- DPCs are transported to the repository where they are repackaged into waste packages of a specified size, except for the DPC direct disposal cases, for which no repackaging would be done.
- The waste packages (or DPCs) are emplaced in the repository as soon as their thermal output is at or below the specified emplacement power limit.
- Waste packages are loaded using a blending algorithm in which cooler assemblies are mixed with hotter assemblies to achieve desired thermal output (except for the DPC direct disposal cases).

The focus of the analysis was on the achievable repository emplacement rate (constrained by thermal limits and throughput of upstream facilities) and the duration of repository emplacement operations.

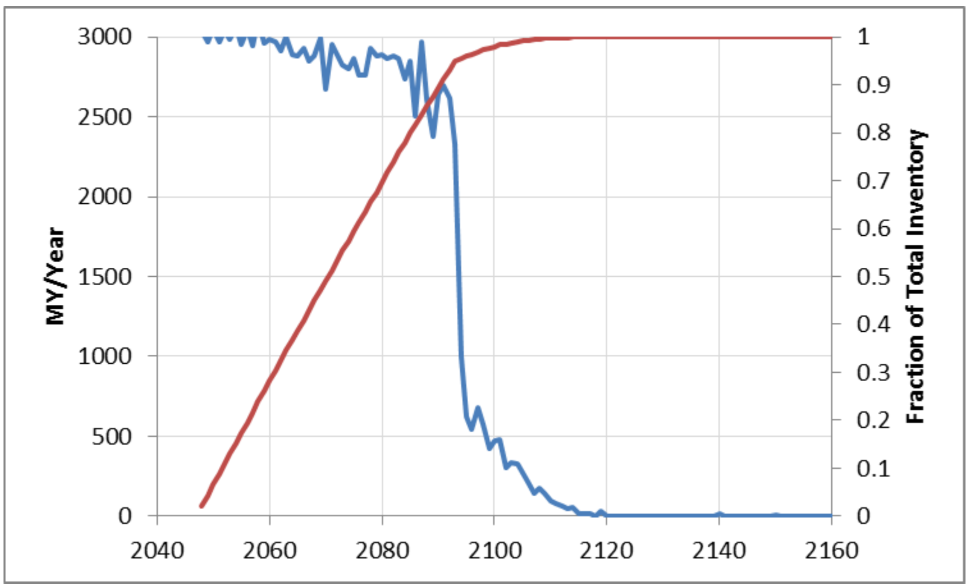
DISCUSSION OF RESULTS

Representative results are shown in Fig. 1 and Fig. 2, which plot the emplacement rates for each year (blue curves), and cumulative fractions of total inventory disposed (red curves), Concepts 1 and 2, and Concept 7, respectively. The results for the other concepts, except Concept 3, are similar to Fig. 1.



Blue curve: annual rate. Red curve: cumulative rate.

Fig. 1. Emplacement Rate and Cumulative Disposal, for Disposal Concepts 1 and 2 (4PWR/9BWR size packages in crystalline and argillaceous media; emplacement power limit 1.7 kW).



Blue curve: annual rate. Red curve: cumulative rate.

Fig. 2. Emplacement Rates and Cumulative Disposal, for Disposal Concept 7 (DPC direct disposal in salt; emplacement power limit 11.5kW).

For most of the disposal concepts, an emplacement rate of 3,000 MTU/year can be maintained during the first 44 years of the repository operations. A total of 99% of SNF inventory can be emplaced during 45 to 54 years of the repository operations. The remaining 1% of the inventory (1,400 MTU) could require some additional aging before emplacement, or smaller (or de-rated) waste packages.

The direct disposal of DPCs in Concept 7 (Fig. 2) takes slightly longer and results in lower emplacement rates during early operations.

The emplacement rate in Concept 3 (12PWR/21BWR size packages; emplacement power limit 1.7 kW) varies from 500 to 1,800 MTU/year during the first 170 years of operations and drops significantly after that (Fig. 3). Emplacing 99% of the inventory requires 197 years. Concept 3 is unique in that larger packages are used with temperature-sensitive backfill, so longer aging times are needed.

Two additional variations were considered for Concept 3 to evaluate how the thermal management approach could be changed to accelerate repository operations and closure. In the first variation, 50% of the total inventory was emplaced in 12PWR/21BWR size packages and 50% was emplaced in smaller 4PWR/9BWR size packages. In the second variation, 26% of the total inventory was emplaced in 12PWR/21BWR size packages and 74% was emplaced in 4PWR/9BWR size packages. The time required to emplace 99% of the total inventory was reduced by 51 years in the first case and by 79 years in the second case (Fig. 4). Even for the second variation with mostly smaller waste packages, a long repository operational time (118 years) would be needed.

Note that in all simulations the total inventory is transported to the repository during the first 81 years from the start of operations.

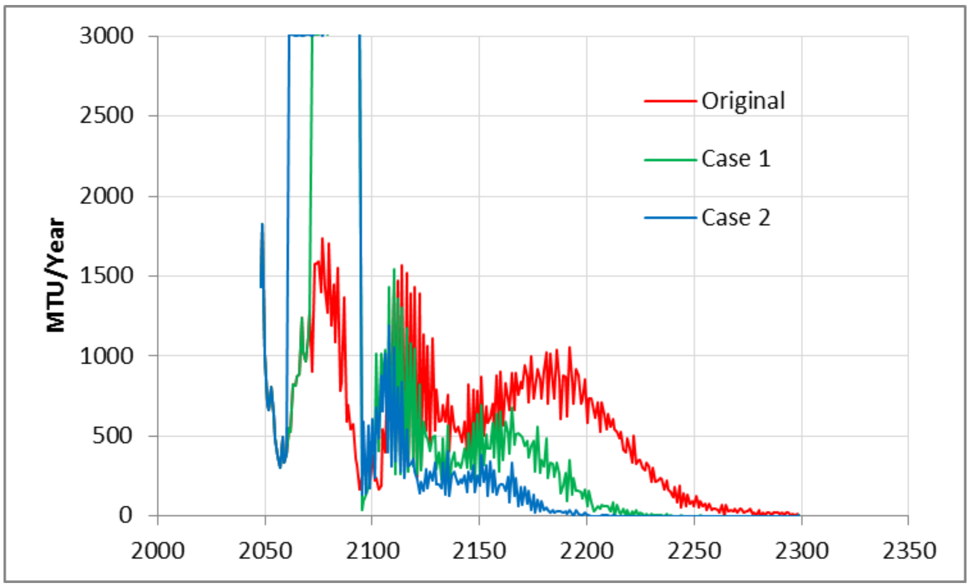
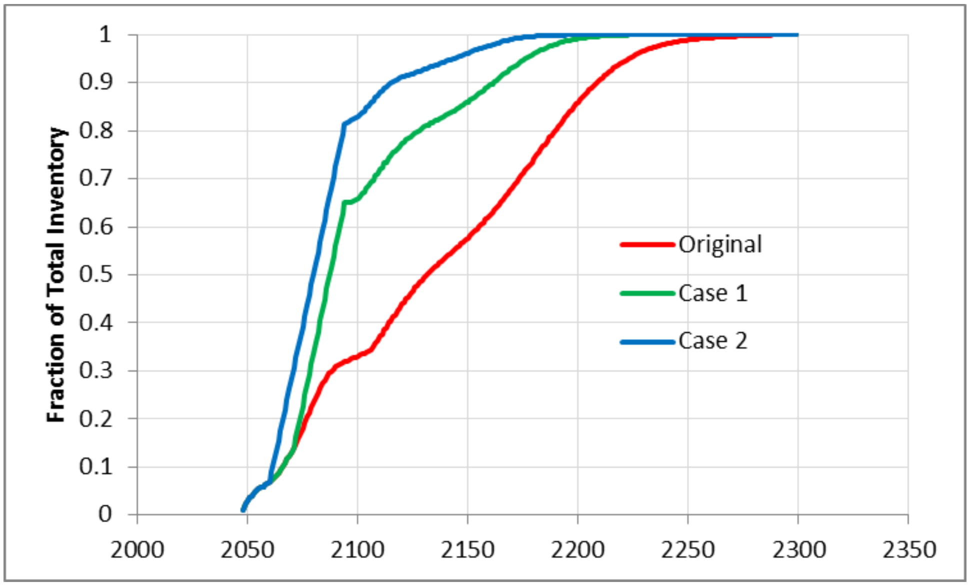


Fig. 3. Emplacement Rates for Disposal Concept 7 (DPCs, 11.5kW).



Case 1: 50% of inventory in 4PWR/9BWR. Case 2: 74% of inventory in 4PWR/9BWR

Fig. 4. Emplacement Rates for Disposal Concept 3 (12PWR/21BWR, 1.7kW).

DISPOSAL COST EXAMPLES

Some examples of ROM disposal cost estimates are provided below to demonstrate the differences due to geologic media and waste package size.

The ROM disposal cost ($Cost_{disp}$) was estimated as:

$$Cost_{disp} = CB_{media} + N_{WP} \cdot CWP_{media} \text{ ,} \qquad \text{(Eq.1)}$$

where CB_{media} ($M) is the base disposal cost specific to a geologic media, N_{WP} is the number of waste packages, and CWP_{media} ($M) is geologic media specific disposal cost per waste package. This simplified approach to cost estimation was developed specifically for system analysis, and is based on more detailed estimates [8].

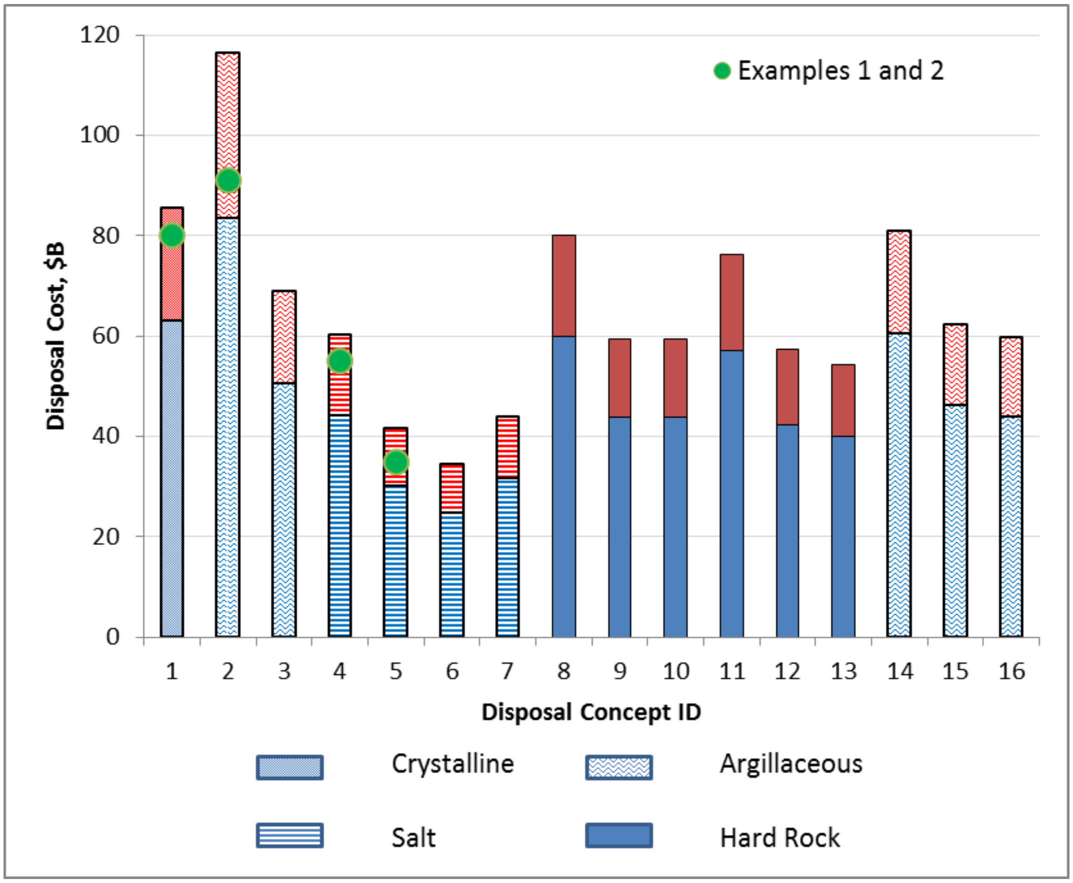
Example 1: Same Waste Package Size (4PWR/9BWR) but Different Media (Crystalline and Argillaceous)

This example compares Concepts 1 and 2 [1], which are enclosed modes for crystalline and argillaceous rock, respectively. The base disposal cost CB_{media} for both types of media was assumed to be $7.5B. The number of waste packages generated in Concepts 1 and 2 would be the same (81,885) with the same emplacement power limit (1.7 kW). The disposal cost per waste package was assumed to be $0.885M for crystalline and $1.025M for argillaceous media. Applying Eq. 1 gives total disposal cost of $80B for crystalline (Concept 1) and $91B for argillaceous media (Concept 2).

Example 2: Different Waste Package Sizes (4PWR/9BWR and 12PWR/21BWR) but Same Media (Salt)

This example compares two salt concepts: Concepts 4 and 5 [1]. These concepts differ only with respect to waste package size, which is 4PWR/9BWR (Concept 4) and 12PWR/21BWR (Concept 5). The emplacement thermal power limit is 2.2 kW for Concept 4 and 5.5 kW for Concept 5. The number of waste packages is 81,885 in Concept 4 and 25,730 in concept 5. The base disposal cost for hard rock media was assumed to be $8B. The disposal cost per waste package was assumed to be $0.575M for Concept 4 and $1.06M for Concept 5. Applying Eq. 1, the disposal cost is $55B for 4PWR/9BWR waste packages and $35B for 12PWR/21BWR packages.

The cost estimates in the above examples are compared in Fig. 5 to the generic repository cost estimates derived in [8] for 16 repository concepts. ROM estimates such as these are intended for relative comparison, and have uncertainty on the order of 30%.



Blue color: lower cost limit. Red color: upper cost limit.

Fig. 5. ROM Disposal Cost for Different Media and Waste Package Capacities.

CONCLUSIONS

The summary of enveloping emplacement rates and duration of operation for 16 Disposal Concepts is presented in Table II.

The logistical simulation demonstrated that nearly all the disposal concepts (except Concept 3) are very similar with regard to the emplacement rates and durations of operations. The emplacement rate goal of 3,000 MTU per year can be maintained (or nearly so) during the first 44 years of repository operations. Most of the inventory (99%) can be emplaced during 45 to 54 years of repository operations.

The remaining 1% of the inventory (1,400 MTU) could require some additional aging or packaging in smaller waste packages.

TABLE II. Summary of Enveloping Emplacement Rates and Duration of Operation for 16 Disposal Concepts.

Concept		Waste Package Capacity (PWR/BWR)	140,000 MTU Repository	
			Emplacement Rate (MTU/year)	**Duration of Operation (yr)**
1	**Crystalline (enclosed)**	4/9	3,000	46
2	**Argillaceous (enclosed)**	4/9	3,000	46
3		12/21	1,700	~200 [A]
4	**Salt (enclosed)**	4/9	3,000	46
5		12/21	3,000	46
6		21/44	3,000	46
7		DPC	3,000	54
8	**Hard rock unsaturated (open)**	12/21	3,000	46
9		21/44	3,000	46
10		DPC	3,000	54
11	**Hard rock saturated (open)**	12/21	3,000	46
12		21/44	3,000	46
13		DPC	3,000	54
14	**Argillaceous (open)**	12/21	3,000	46
15		21/44	3,000	46
16		DPC	3,000	54

Note: [A] Shorter durations can be achieved by substituting smaller 4PWR/9BWR packages as indicated in Figure 4.

The emplacement rate for Concept 3 (a unique concept with relatively large packages and temperature sensitive backfill) varies from 500 to 1,800 MTU per year during the first 170 years of operations, and drops significantly after that. Emplacing 99% of the inventory requires 197 years. The duration of operations can be significantly reduced if 50% or more of SNF inventory is emplaced in 4PWR/9BWR waste packages.

ROM disposal concepts were estimated using a previously developed methodology [8], for disposal of 140,000 MTU of commercial SNF. The upper limit for disposal cost (91$B) is for small (4PWR/9BWR) packages in argillaceous media, while the lower limit ($35B) is for direct disposal of large DPC-based packages (32PWR size is assumed) in salt.

This work has provided a sample of logistical and cost performance that could be expected for a range of SNF disposal concepts in different geologic host media, and with different types of waste packages. It shows that many disposal solutions are possible, given thermal constraints, within a repository operational period of approximately 50 years. The estimated costs for these solutions vary by an overall factor of 2 to 3, depending primarily on the number of waste packages.

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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.