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Logistical Simulation of Spent Nuclear Fuel Disposal in a Salt Repository with Low Temperature Limits

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ABSTRACT

Two logistical modeling cases evaluated the relative cost, schedule, and thermal results for strategies that would limit peak salt temperature in a spent-fuel repository to 90°C and 150°C. Runs with the code CALVIN 4.0 show that these low thermal limits are logistically feasible for a salt repository using relatively small waste packages (4-PWR/9-BWR or 12-PWR/24-BWR sizes). Attainment of low-thermal goals was represented using instantaneous waste package thermal power limits at emplacement (3,200 W and 6,800 W) which came from a correlation between package power and peak salt temperature that was developed by a previous study using the finite element method.

Low-thermal goals (90°C or 150°C peak temperatures) can be achieved on the same schedule, but with significantly greater cost for the 90°C (3,200 W) case. Lag storage and utility costs are similar for both cases. The cost difference is dominated by the repository cask cost, and the larger number of waste packages required (more than 86,000 4-PWR size casks for the 90°C case). Note that these cost values are relative, do not include the underground disposal facility, and have not been compared to, or reconciled with other estimates.

ACKNOWLEDGEMENTS

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ACRONYMS

BWR	Boiling Water Reactor
DPC	Dual-Purpose Canister
MTU	Metric Tons Uranium
PWR	Pressurized Water Reactor
W	Watts
WP	Waste Package

1.0 INTRODUCTION

Geologic disposal of spent nuclear fuel (SNF) from the fleet of operating commercial reactors in the U.S., closely depends on approaches for management of waste-generated heat. Temperature limits (or temperature-time exposure constraints) associated with engineered or natural materials, can be met using decay storage (before emplacement underground), and waste package size and capacity. Temperature limits for various geologic media have been surveyed (Hardin et al. 2012) and salt is considered to have high tolerance to peak temperature (up to 200°C or hotter).

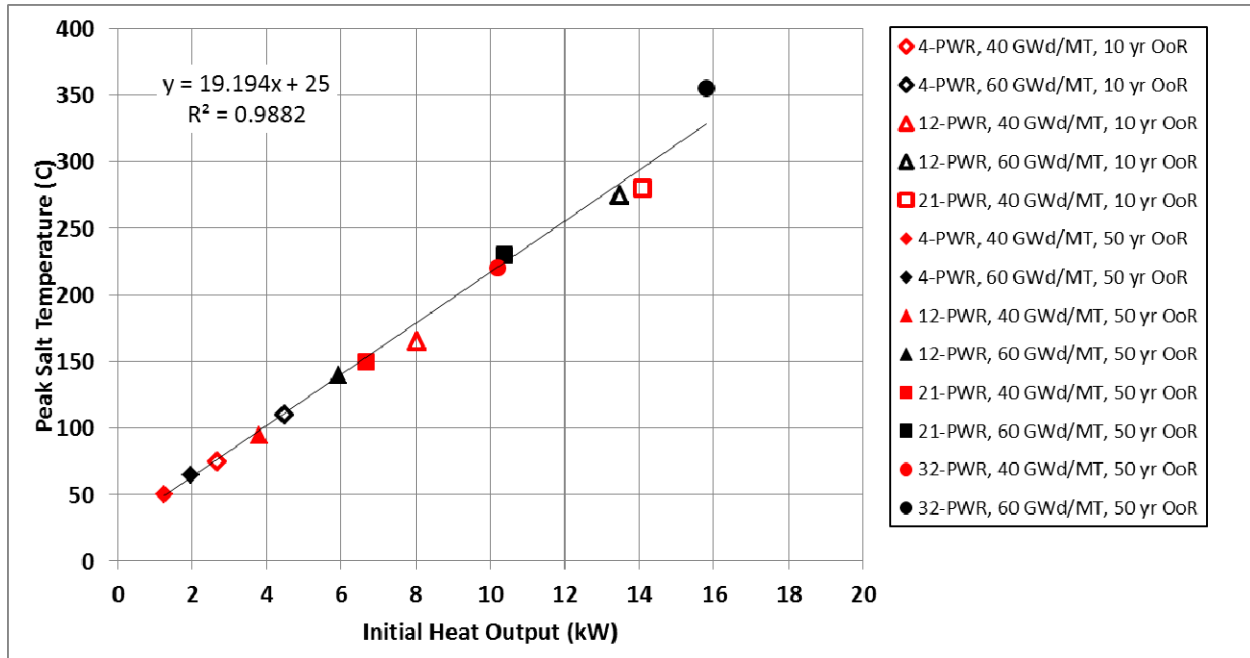
Repository performance assessment relies on screening of an exhaustive list of potentially important features, events, and processes (FEPs) related to waste isolation. There may be hundreds of FEPs, many of them temperature dependent, for which screening analysis is required for repository performance assessment. Those screening analyses (and the models used) can be simplified by modifying thermal management practices to lower temperatures, at least initially when the repository is being licensed, constructed, and loaded with waste for the first time. This study evaluates the feasibility (including cost and schedule) of re-packaging SNF into smaller, cooler waste packages to limit peak salt temperature in a repository. The CALVIN logistics code (BSC 2003) is used to simulate SNF selection at power plants, transport to a repository, re-packaging, and emplacement underground.

Output from these simulations includes: 1) the numbers of packages needed for PWR and BWR SNF, 2) the heat output of those packages, 3) the transport infrastructure needed, and 4) the amount of lag storage needed at the repository for additional SNF aging to meet waste package power limits.

Thermal management constraints are implemented in these simulations using the heat output of waste packages when they are emplaced, which is correlated with peak salt temperature (Figure 1). Peak salt temperature is a transient that occurs at the waste package surface where it contacts the salt, within a few years after emplacement. It is not the only possible constraint; other limits could apply to average areal thermal loading, peak pillar temperature (between packages), etc. The peak salt temperature does represent the influence of thermal conditions on the near field host rock, an important isolation barrier in the salt repository concept. The correlation was developed from finite-element simulations of various waste package sizes (5 m long, and 0.82 to 2 m in diameter) each with a specified SNF capacity, and various SNF age and burnup specifications (Clayton et al. 2012; Hardin et al. 2012). The quality of this correlation shows that instantaneous package heat output is the predominant influence, and that the rate of decreasing thermal output and the package radius, are second-order.

Two cases were analyzed for this study, approximating conditions that give rise to peak salt temperatures of 90°C and 150°C, using waste package power limits of 3,200 and 6,800 W respectively, at emplacement (Figure 1). The 90°C limit is well below the boiling temperature of free water or NaCl brine, and could limit processes such as thermally activated salt creep, localized corrosion, etc., that can proceed faster at higher temperatures. The 150°C limit could limit processes such as salt creep that are active at higher temperatures. For this study these limits are used as targets for evaluating thermal management strategies, without exploring any specific aspects of FEP temperature sensitivity.

Logistical Simulation of Spent Nuclear Fuel Disposal in a Salt Repository with Low Temperature Limits



NOTE: This figure is reproduced from Figure D.5 from Hardin et al. (2012)

Figure 1. Correlation between Waste Package Heat Output and Peak Salt Temperature.

2.0 EFFECTS OF HEAT LIMITS ON WASTE EMPLACEMENT

This analysis was done using a modified version of the computer code CALVIN 4.0 (BSC 2003). The modifications included improved and updated cost analysis, and incorporation of re-packaging at a centralized storage into the waste management system. The modified CALVIN 4.0 is one module of a transportation-storage logistics (TSL) modeling tool developed for system architecture studies in the Used Fuel Disposition R&D campaign.

CALVIN 4.0 was selected for this study because it simulates SNF inventory from reactor-discharge, throughout dry or wet storage, transport, blending of SNF assemblies to achieve desired waste package thermal power, and emplacement underground. Accordingly, the characteristics of individual waste packages such as average SNF age or burnup, are simulated at emplacement, with reasonable uncertainty. SNF is “picked up” at reactor sites using one of several optional selection criteria including oldest fuel first (OFF), youngest fuel first (YFF), and YFF with a specified minimum age. The OFF criterion is used in this study because it ensures that the coolest available SNF is received at the repository, thus allowing disposal operations to commence soonest, and enabling use of larger packages where appropriate. The minimum fuel age for pickup is 5 years out-of-reactor. CALVIN allows SNF to be selected from fuel pools or dry storage first; for this study SNF is selected first from the pool at a particular site, and then from dry storage. The OFF principle is also used to select SNF from among different reactor sites.

For a specified thermal limit, CALVIN uses a blending algorithm to load waste packages. SNF assemblies are selected from a small inventory received and stored at the repository, to meet but not exceed the specified package thermal power limit. The waste package size is selected from a priority list starting with the first preference, and proceeding to second or third preferences if the SNF assemblies on hand cause the waste package power to exceed the limit. Later preferences may be smaller packages, or de-rated packages in which one or more assemblies are simply not loaded. If the assemblies on hand always result in a package that is cooler than the limit, the hottest configuration is selected using the first package preference. Waste package lists are input for both PWR and BWR SNF. For this study the first preferences correspond to 4-PWR and 12-PWR sizes, for the 90°C and 150°C cases, respectively.

Both scenarios considered in this analysis assume that SNF will accumulate at reactor sites until 2025, when the repository will begin accepting waste. SNF would be transported from reactor sites directly to the repository without intermediate steps, such as consolidated storage. The SNF would be emplaced as soon as it can be loaded into a waste package. Prior to 2025 the SNF would be stored in fuel pools, until the pools are full. Once the fuel pool at a particular reactor site is full, CALVIN selects SNF for dry cask storage at the same reactor site using specified cask limits. Eventually, as in this study, all the SNF from fuel pools and dry storage is transported to the repository.

It is assumed the hypothetical repository is located in the Permian Basin (where the Waste Isolation Pilot Plant is situated) or immediate vicinity. A specified location is required as an input for CALVIN calculations related to transportation. This selected location has no impact on SNF blending to load waste packages, and it has only minor impacts on cost and schedule. Any other location could have been used here with very similar results.

The assumed throughput rate (“waste acceptance rate”) is 3,000 MTU/yr, which is typical for other studies of this type (for example, DOE 2008). The total SNF inventory after shutdown of the existing fleet of operating commercial reactors is 138,735 MTU (Kalinina 2012). This value was obtained assuming licensed extension of the full-power operating life for all 104 operating reactors to 60 years, with 0% annual increase in average SNF burnup and no new builds.

The fuel is transported to the repository either by truck (a few reactor sites that are appropriately represented in the CALVIN database) or by dedicated rail both ways (most reactor sites, also represented in the database). Heavy-haul and barge transportation is used to transport fuel from reactor sites to railheads for 25 sites where direct access to rail is not available.

The inventory of dry storage casks is defined based on current practices at the reactor sites. For projected dry storage to be implemented in the future, standard dual-purpose canisters (DPCs) are assumed (32-PWR or 68-BWR capacity).

The results for the two heat limit cases are presented in Section 2.1 and 2.2.

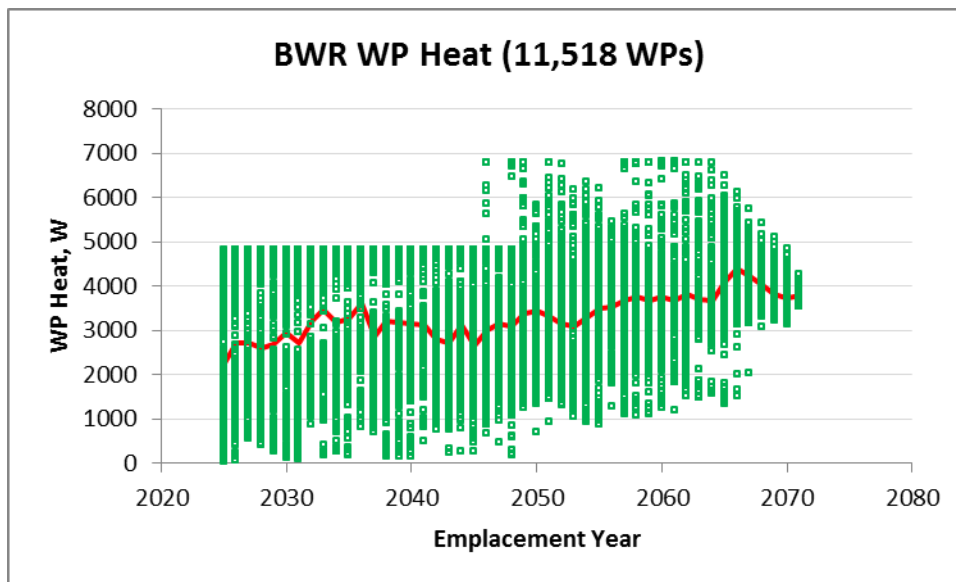
2.1 Waste Package Heat Limit of 6,800 W (150°C)

For this case the entire SNF inventory could be emplaced in 46 years (from 2025 through 2071) in 28,684 waste packages (11,518 BWR and 17,166 PWR). Heat output for the blended waste BWR and PWR packages, as functions of calendar time, is shown in Figures 2 and 3, respectively. These figures show every waste package with a separate symbol, so clustering of packages near the thermal limit is not evident. In fact, waste package thermal power is typically clustered near the limit, with a few colder packages defining the lower range.

The first preference for waste package size specified in this case was 12-PWR/24-BWR. The heat output of the BWR packages is below 5,000 W until 2045. Starting from 2046, more BWR waste packages are just below the specified heat limit of 6,800 W. The heat output of a number of PWR waste packages is just below the heat limit during all the period of emplacement. During 2054 to 2056, only a few PWR packages were emplaced due to the limited number of older and colder PWR assemblies available at the repository.

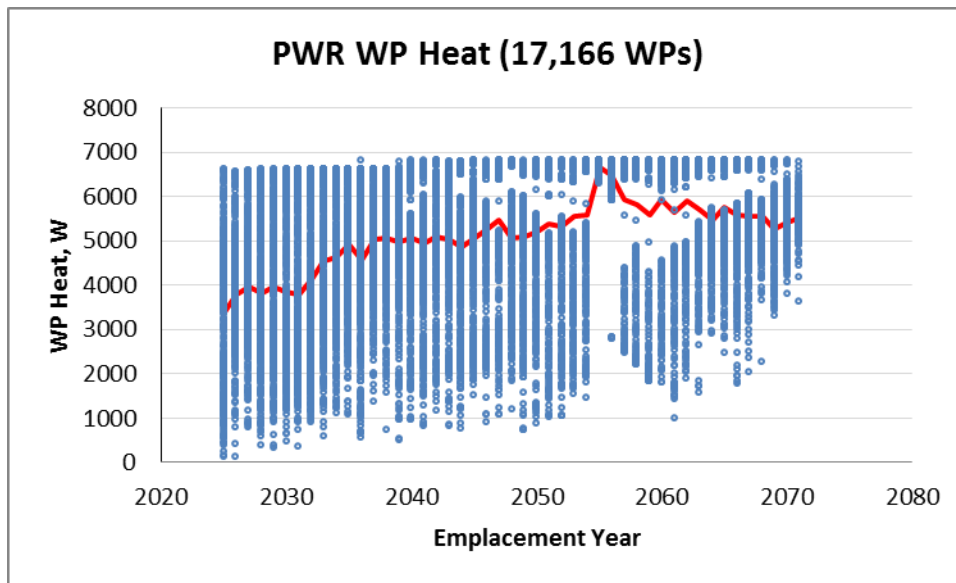
The calculated peak salt temperatures, using the correlation shown in Figure 1, are shown in Figures 4 and 5 for BWR and PWR packages, respectively. Because of the linear correlation relationship, these plots scale exactly to Figures 2 and 3.

The numbers of BWR and PWR waste packages emplaced each year are plotted in Figures 6 and 7, respectively. The number of BWR waste packages ranges from 33 to 356 with an average of 245/yr, while the number of PWR waste packages ranges from 113 to 435 with an average of 365/yr.



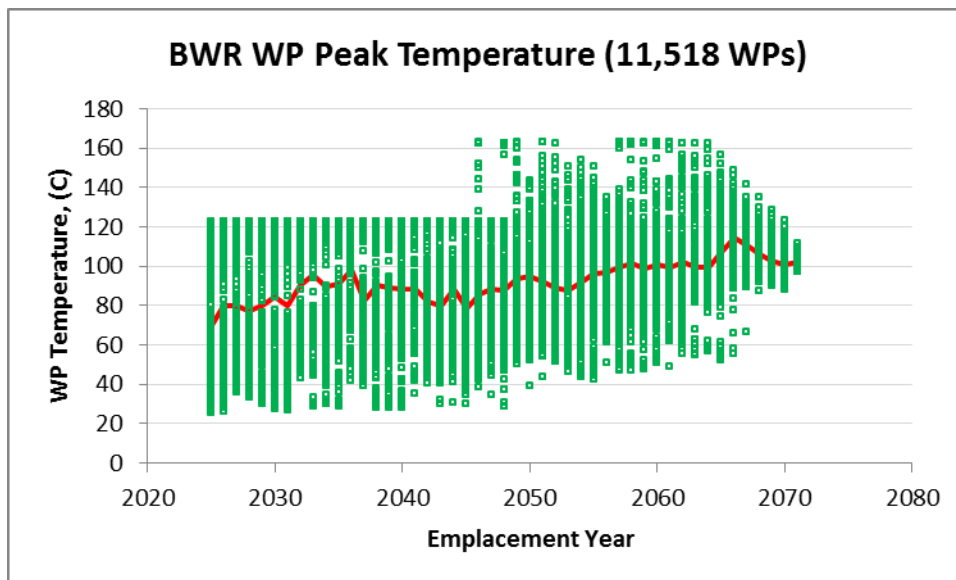
NOTE: Red line shows average heat output

Figure 2. BWR Waste Package Heat Output at Emplacement, Heat Limit 6,800 W



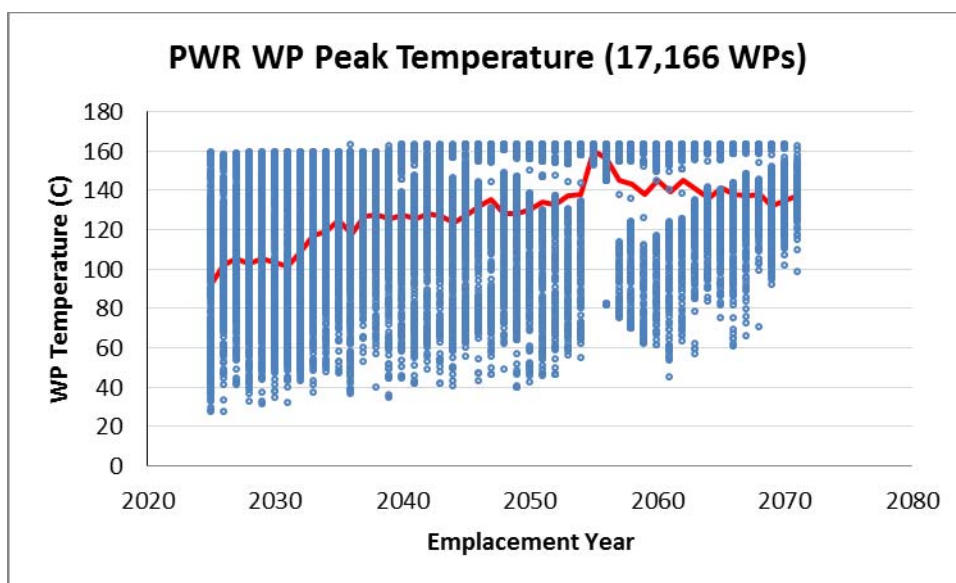
NOTE: Red line shows average heat output

Figure 3. PWR Waste Package Heat Output at Emplacement, Heat Limit 6,800 W



NOTE: Red line shows average peak temperature

Figure 4. BWR Waste Package Peak Temperature at Emplacement, Heat Limit 6,800 W



NOTE: Red line shows average peak temperature

Figure 5. PWR Waste Package Peak Temperature at Emplacement, Heat Limit 6,800 W

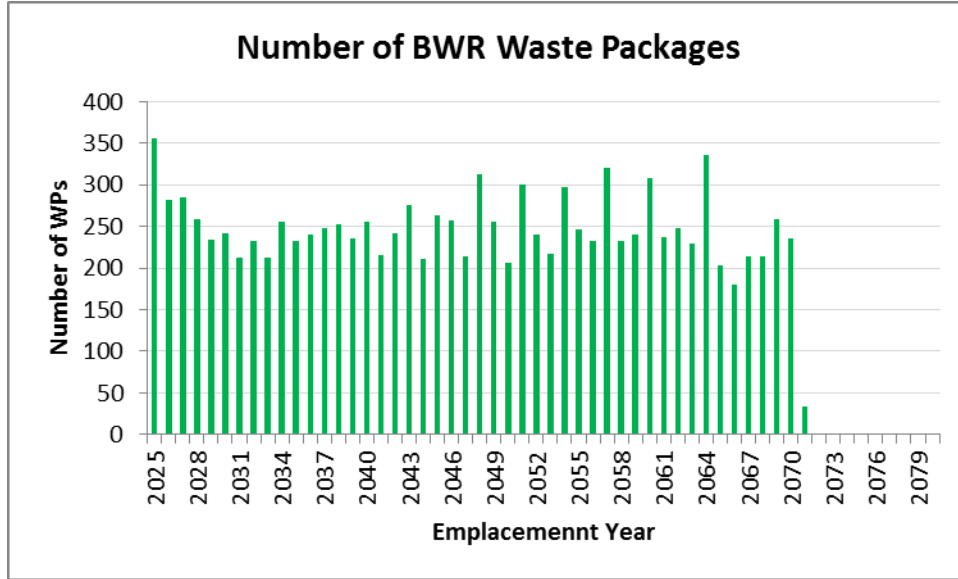


Figure 6. Number of Emplaced BWR Waste Packages, Heat Limit 6,800 W

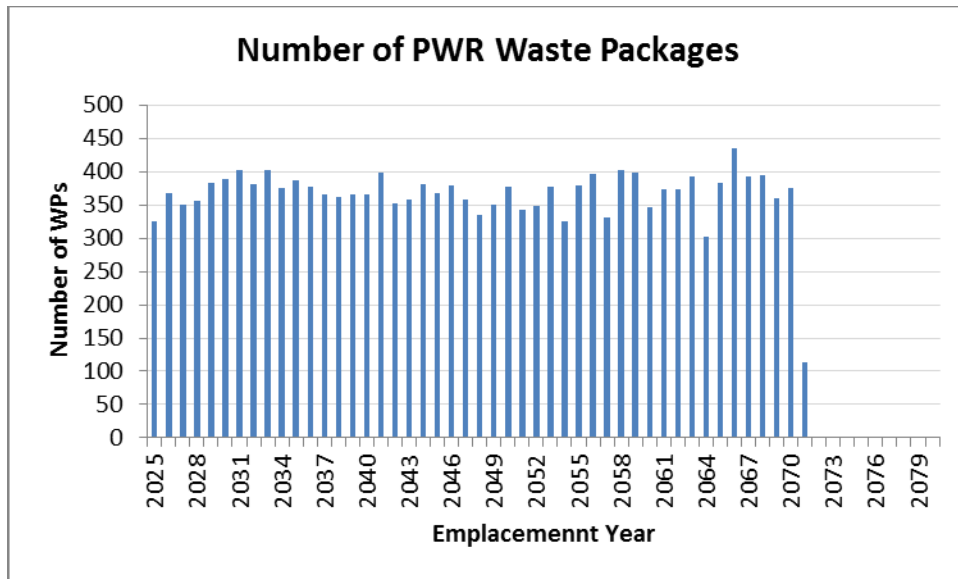


Figure 7. Number of Emplaced PWR Waste Packages, Heat Limit 6,800 W

Figure 8 shows the lag storage capacity needed for PWR and BWR SNF that was too hot to be loaded in waste packages, and for which additional decay storage was needed. Lag storage for BWR SNF is very small, while that for PWR SNF is more significant from 2053 to 2061. The maximum PWR lag storage is 963 assemblies.

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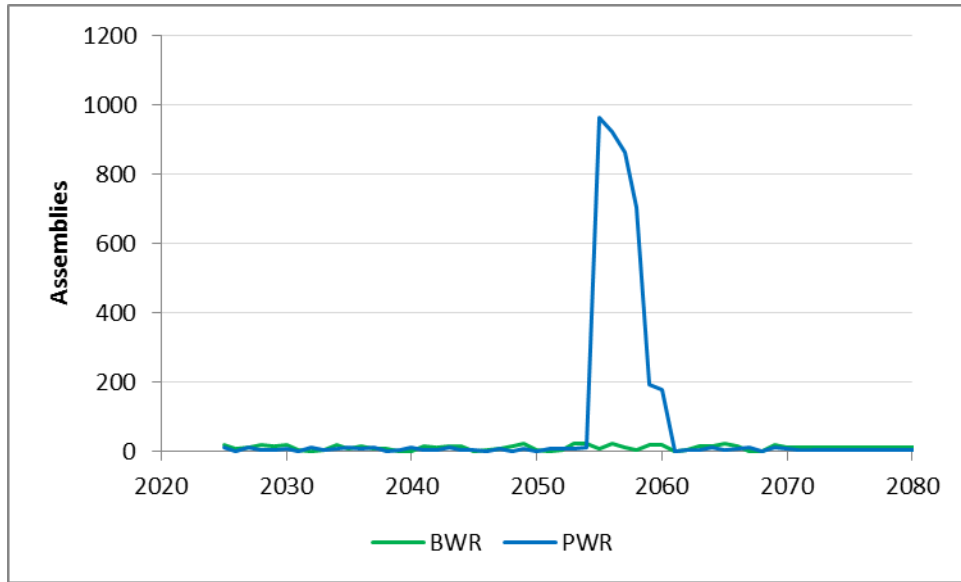


Figure 8. PWR and BWR Assemblies in Lag Storage, Heat Limit 6,800 W

The annual emplacement rates for PWR and BWR SNF are shown in Figure 9. The PWR waste package amounts fluctuate around 2,000 MTU/yr and the BWR waste package amounts fluctuate around 1,000 MTU/yr.

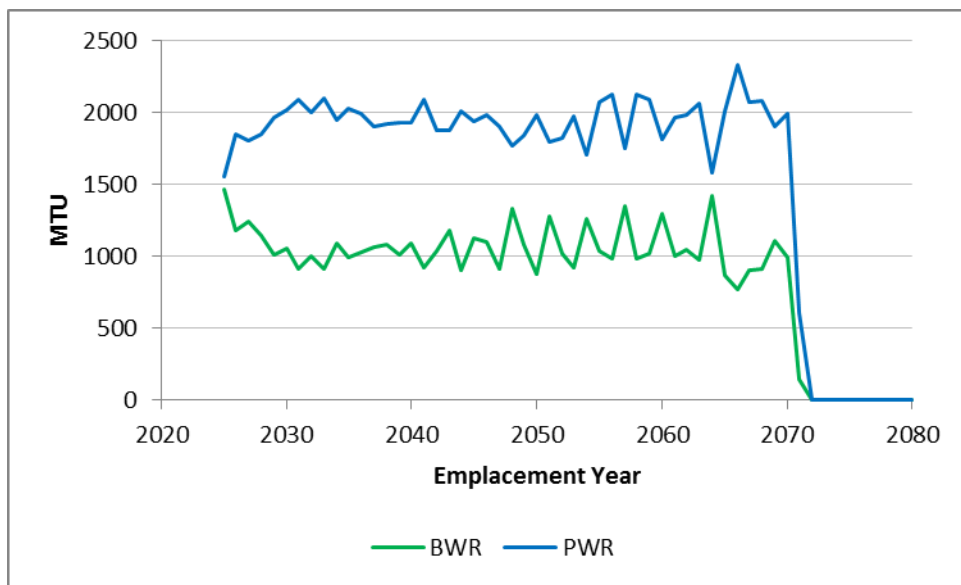


Figure 9. MTU Emplaced in PWR and BWR Waste Packages, Heat Limit 6,800 W

Operational costs calculated by CALVIN are shown in Figure 10. These include costs incurred by the operating utilities for fuel management, costs for transport to the repository, and costs for packaging prior to disposal. The modified version of CALVIN incorporates an improved algorithm of the utility costs and the recent cost data.

The total utility costs in Figure 10 include the following:

- Initial construction costs for a dry storage facilities, assumed to be incurred in the first year of dry storage.
- Dry storage facility maintenance costs at operating sites
- Dry storage facility maintenance costs at shutdown sites
- Pool maintenance at shutdown sites
- Dry storage loading costs
- Dry storage cask and overpack purchase costs
- Loading canisters from dry storage for transportation
- Loading bare fuel for transportation

Transportation costs in CALVIN are calculated using a simplified approach and the cost data were not recently updated.

Repository cask costs are calculated as the number of casks multiplied by a unit cask cost. The other costs, such as loading waste package canisters and other processing costs are not included in this category.

Cost results are presented only for relative comparisons. These figures do not include all the costs of SNF management and disposal, only those incurred upstream from the underground disposal facility, and with the greatest potential to differ between the cases considered. As seen from Figure 10, transportation cost is a small portion of total cost, and the utility costs are the major cost component. The utility costs are at their maximum from 2039 to 2054 due to pool maintenance cost at the shutdown sites. The costs decrease after all the pools are unloaded into dry storage. Cost profiles are highly variable for utility costs and nearly constant for repository cask costs. The overall cost profile generally follows the utility cost profile.

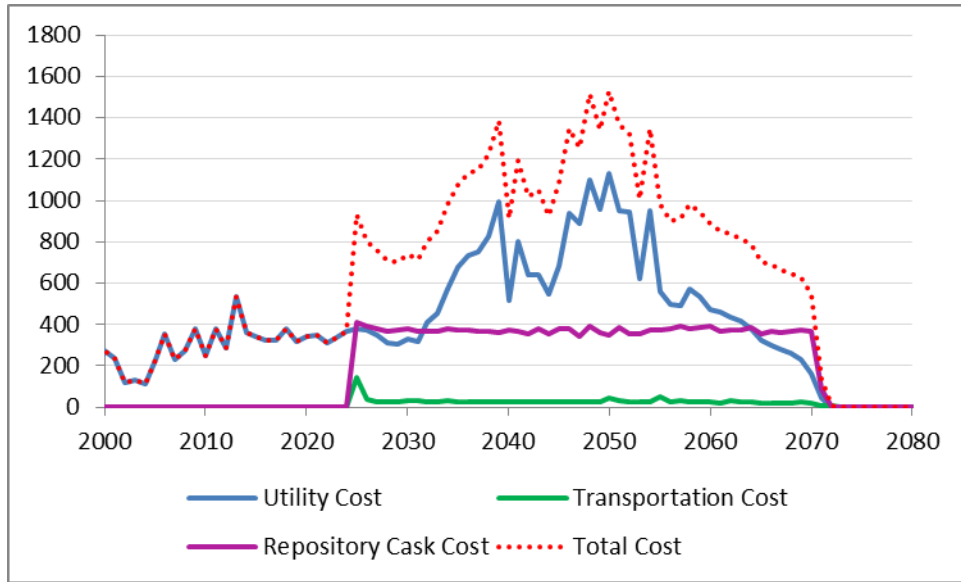


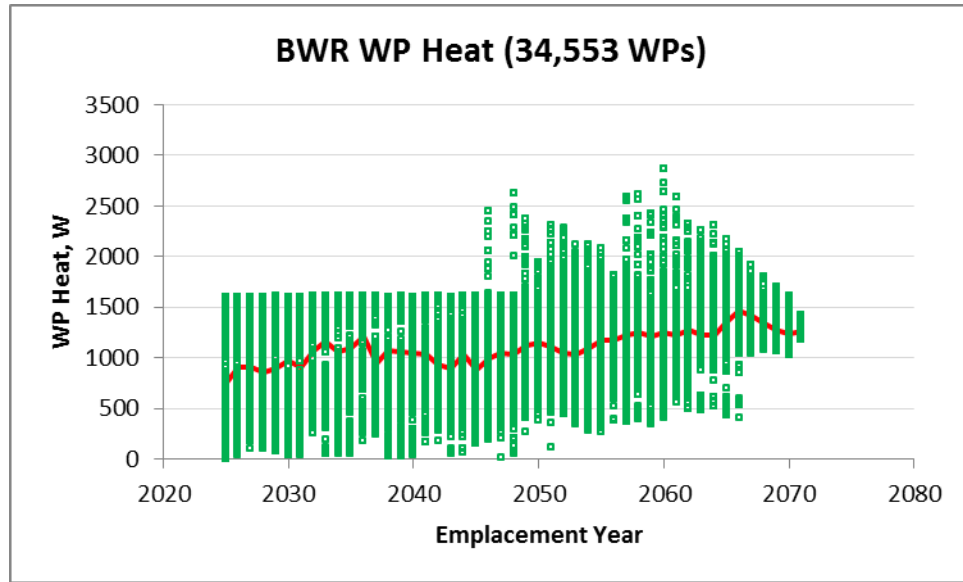
Figure 10. Annual Operating Costs in 2000 Dollars, Heat Limit 6,800 W

2.2 Waste Package Heat Limit of 3,200 W (90°C)

For this case the entire SNF inventory could also be emplaced in 46 years (from 2025 through 2071) in 86,049 waste packages (34,553 BWR and 51,496 PWR). Heat output for the blended waste BWR and PWR packages, as functions of calendar time, is shown in Figures 11 and 12, respectively. Like the 6,800 W case, waste package thermal power is typically clustered near the limit, with a few colder packages defining the lower range.

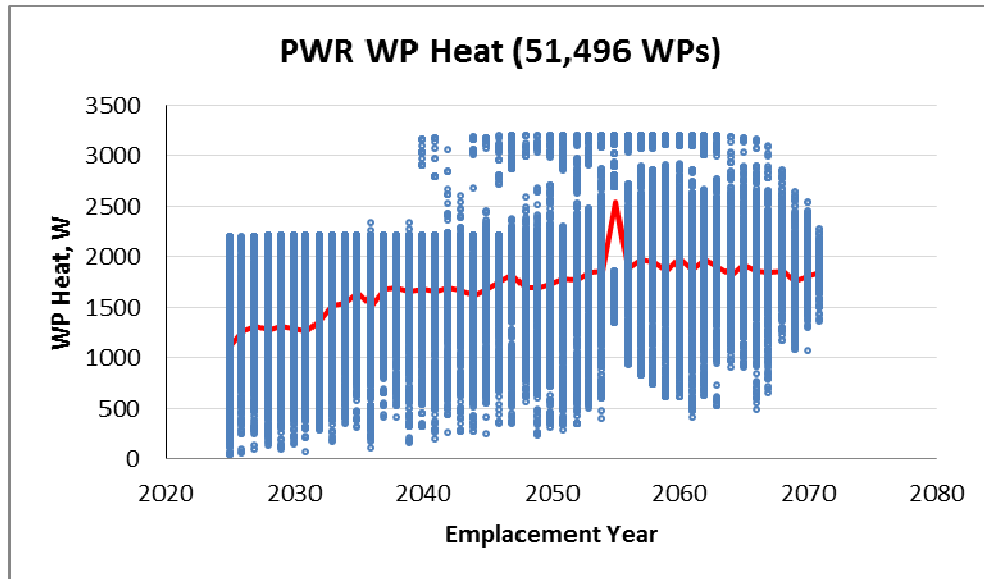
The first preference waste package specified in this case was the 4-PWR/9-BWR size. Larger packages than the 4-PWR-9-BWR could not be used in this case. The heat output of the BWR packages is below 1,600 W until 2045. Starting from 2046, more BWR waste packages are just below the specified heat limit of 3,200 W. The heat output of PWR waste packages is below 2,200 W until 2040, then more of them are at or near the limit of 3,200 W. BWR and PWR waste package peak temperatures are shown in Figures 13 and 14, respectively.

The numbers of PWR and BWR waste packages emplaced each year are plotted in Figures 15 and 16, respectively. The number of BWR waste packages ranges from 99 to 1,070 with an average of 735/yr, while the number of PWR waste packages ranges from 337 to 1,307 with an average of 1,096/yr.



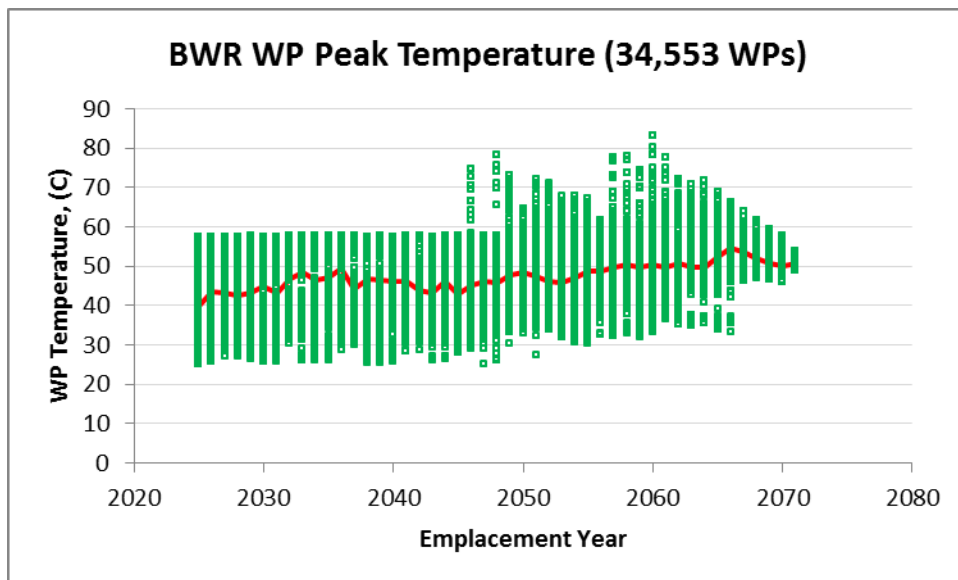
NOTE: Red line shows average heat output

Figure 11. BWR Waste Package Heat Output at Emplacement, Heat Limit 3,200 W



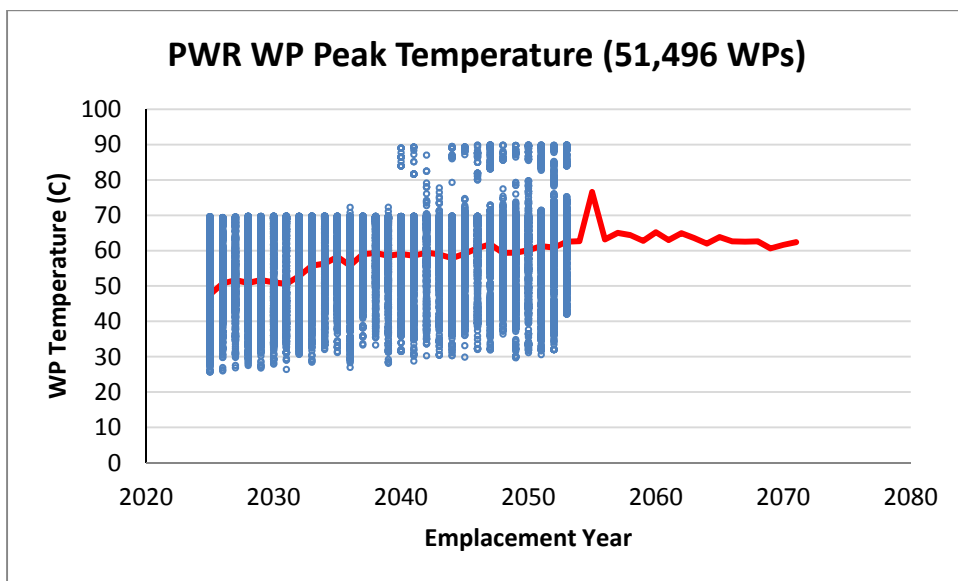
NOTE: Red line shows average heat output

Figure 12. PWR Waste Package Heat Output at Emplacement, Heat Limit 3,200 W



NOTE: Red line shows average peak temperature

Figure 13. BWR Waste Package Peak Temperature at Emplacement, Heat Limit 3,200 W



NOTE: Red line shows average peak temperature

Figure 14. PWR Waste Package Peak Temperature at Emplacement, Heat Limit 3,200 W

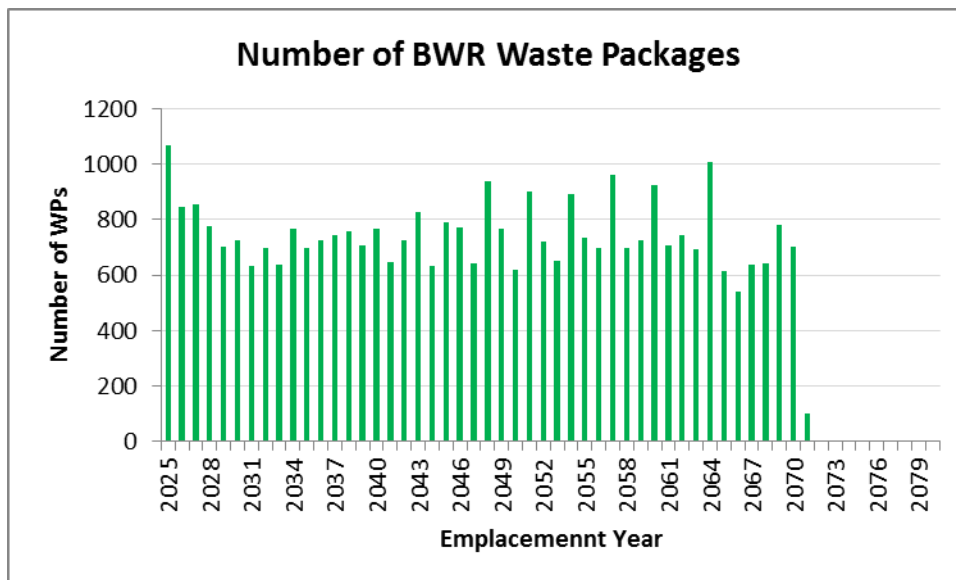


Figure 15. Number of Emplaced BWR Waste Packages, Heat Limit 3,200 W

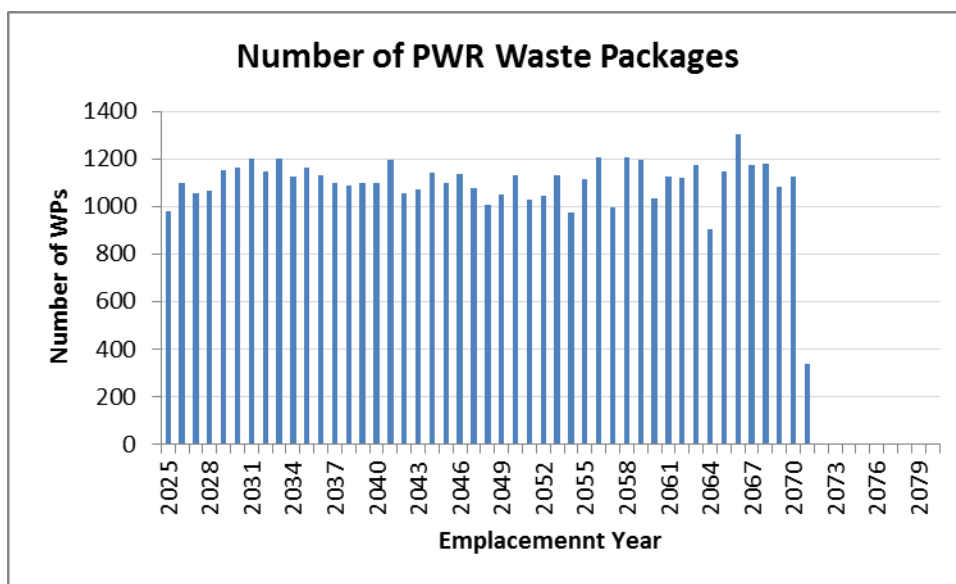


Figure 16. Number of Emplaced PWR Waste Packages, Heat Limit 3,200 W

Figure 17 shows the lag storage capacity needed for PWR and BWR SNF that was too hot to be loaded in waste packages, and for which additional decay storage was needed. Lag storage for BWR SNF is again very small, while that for PWR SNF is more significant from 2053 to 2061. The maximum PWR lag storage is 1,047 assemblies. These results are similar to the 6,800 W case.

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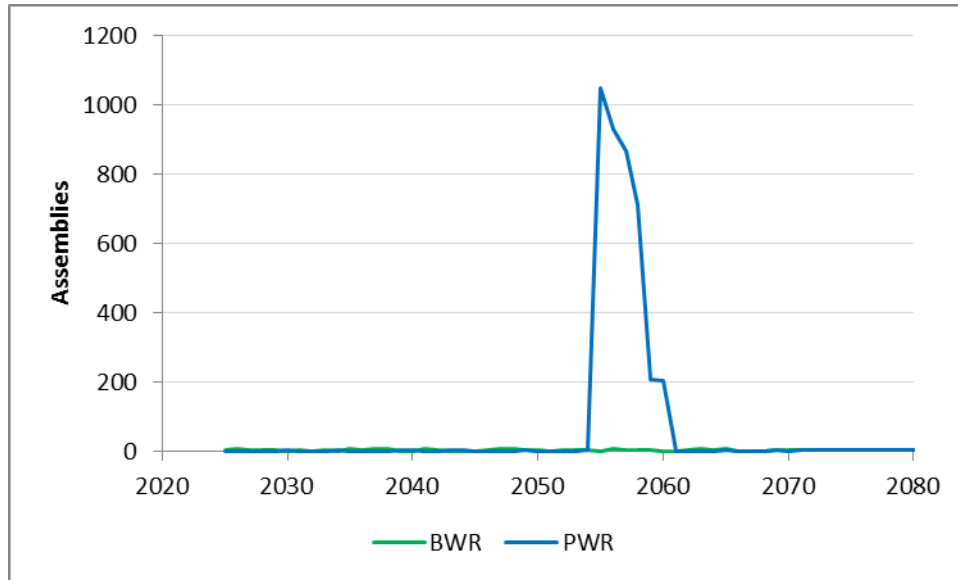


Figure 17. PWR and BWR Assemblies in Lag Storage, Heat Limit 3,200 W

The annual emplacement rates for PWR and BWR SNF are shown in Figure 18. The PWR waste package amounts fluctuate around 2,000 MTU/yr and the BWR waste package amounts fluctuate around 1,000 MTU/yr, same as for the 6,800 W case.

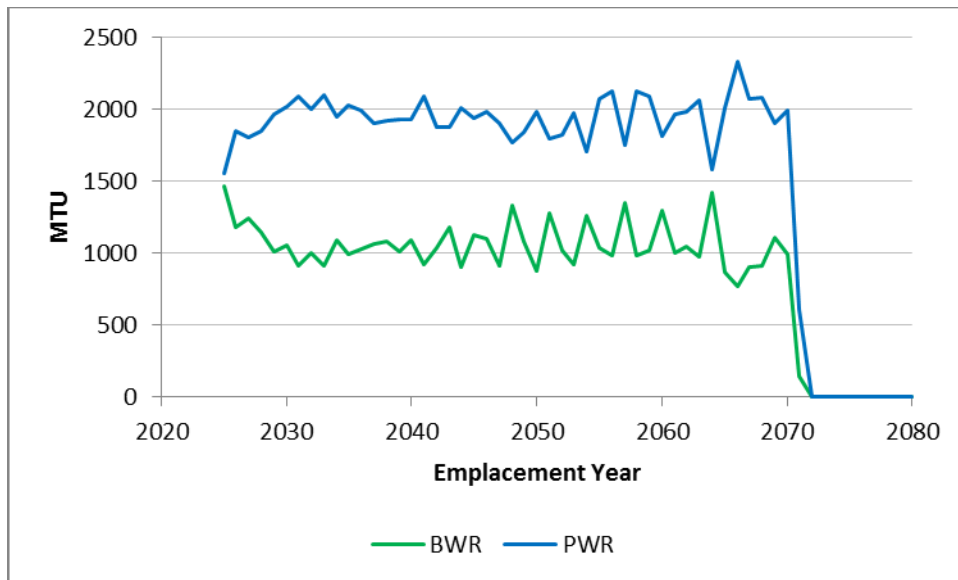


Figure 18. MTU Emplaced in PWR and BWR Waste Packages, Heat Limit 3,200 W

Operational costs for the 3,200 W case are shown in Figure 19. As for the previous case, transportation costs represent a very small portion of the total cost, and repository cask costs are the major cost component. Utility costs are comparable to the repository cask costs only during short periods of time. However, the total cost profile generally follows the utility cost profile.

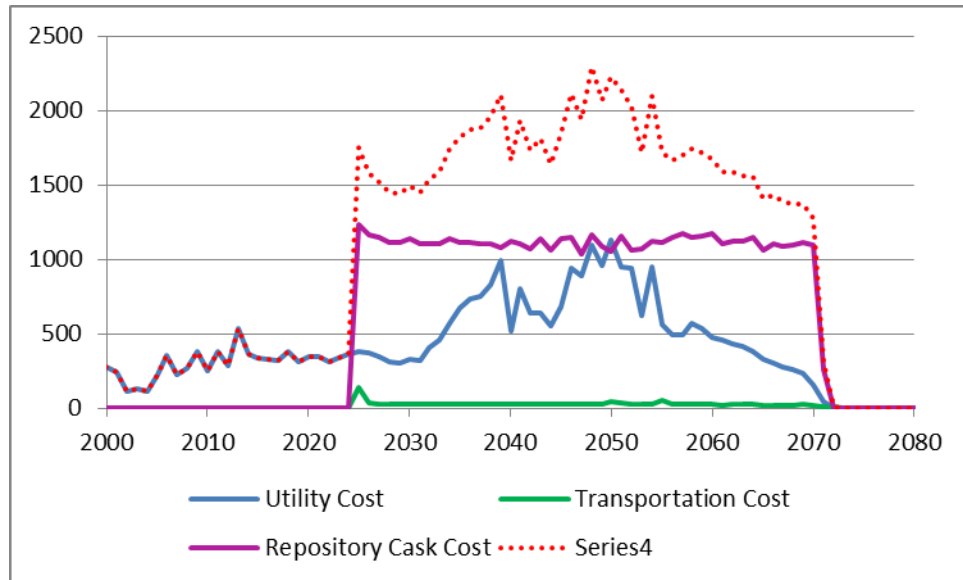


Figure 19. Operational Costs in 2000 Dollars, Heat Limit 3,200 W

3.0 SUMMARY

The results of the analysis are summarized in Table 1. These runs with CALVIN 4.0 show that low thermal limits are logistically feasible for a salt repository using relatively small waste packages (4-PWR/9-BWR or 12-PWR/24-BWR sizes). Low-thermal goals were represented using waste package thermal power limits at emplacement, from a correlation between package power and peak salt temperature that was developed by a previous study (Hardin et al. 2012).

Low-thermal goals (90°C or 150°C peak salt temperatures) can be achieved on the same schedule, but with significantly greater cost for the 90°C (3,200 W) case. Lag storage and utility costs are similar for both cases. The cost difference is dominated by the repository cask cost, and the larger number of waste packages required (Table 1). Note that these cost values are relative, do not include the underground disposal facility, and were not reconciled with other estimates (e.g., Carter et al. 2012).

Table 1. Summary of the Waste Emplacement Analysis (138,735 MTU SNF).

Category	Parameter	Heat Limit 6,800 W (150°C case)	Heat Limit 3,200 W (90°C case)
Costs (\$M)	Utility Cost	35,602 (66%)	35,602 (40%)
	Transportation Cost	1,348 (2%)	1,348 (2%)
	Repository Cask Cost	17,210 (32%)	51,629 (58%)
	Total Cost	54,160	88,579
Number of Waste Packages	# of BWR WPs	11,518	34,553
	# of PWR WPs	17,166	51,496
	Total # of WPs	28,648	86,049
Mean Annual Number of Waste Packages	BWR WPs/year	245	735
	PWR WPs/year	365	1096
Lag Storage Maximum	BWR Assemblies	23	7
	PWR Assemblies	963	1047

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