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System-Level Logistics for Dual Purpose Canister Disposal

Fuel Cycle Research & Development

Prepared for
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Used Fuel Disposition Campaign
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APPENDIX E

FCT DOCUMENT COVER SHEET [1]

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(Participant/National Laboratory Name)

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SUMMARY

The analysis presented in this report investigated how the direct disposal of dual purpose canisters (DPCs) may be affected by the use of standard transportation aging and disposal canisters (STADs), early or late start of the repository, and the repository emplacement thermal power limits. The impacts were evaluated with regard to the availability of the DPCs for emplacement, achievable repository acceptance rates, additional storage required at an interim storage facility (ISF) and additional emplacement time compared to the corresponding repackaging scenarios, and fuel age at emplacement.

The result of this analysis demonstrated that the biggest difference in the availability of UNF for emplacement between the DPC-only loading scenario and the DPCs and STADs loading scenario is for a repository start date of 2036 with a 6 kW thermal power limit. The differences are also seen in the availability of UNF for emplacement between the DPC-only loading scenario and the DPCs and STADs loading scenario for the alternative with a 6 kW thermal limit and a 2048 start date, and for the alternatives with a 10 kW thermal limit and 2036 and 2048 start dates.

The alternatives with disposal of UNF in both DPCs and STADs did not require additional storage, regardless of the repository acceptance rate, as compared to the reference repackaging case. In comparison to the reference repackaging case, alternatives with the 18 kW emplacement thermal limit required little to no additional emplacement time, regardless of the repository start time, the fuel loading scenario, or the repository acceptance rate. Alternatives with the 10 kW emplacement thermal limit and the DPCs and STADs fuel loading scenario required some additional emplacement time. The most significant decrease in additional emplacement time occurred in the alternative with the 6 kW thermal limit and the 2036 repository starting date.

The average fuel age at emplacement ranges from 46 to 88 years. The maximum fuel age at emplacement ranges from 81 to 146 years. The difference in the average and maximum age of fuel at emplacement between the DPC-only and the DPCs and STADs fuel loading scenarios becomes less significant as the repository thermal limit increases and as the repository start date increases. In general, the role of STADs is to store young (30 year or younger) high burnup (45 GWD/MTU or higher) fuel.

Recommendations for future study include detailed evaluation of the feasible alternatives with regard to the costs and factors not considered in this analysis, such as worker dose, dose to members of the public, and economic benefits to host entities. It is also recommended to conduct an additional analysis to evaluate the assumption regarding the transportability and disposability of DPCs for the next iteration of the direct disposal of DPCs study.

CONTENTS

FIGURES

TABLES

SYSTEM-LEVEL LOGISTICS FOR DUAL PURPOSE CANISTER DISPOSAL

1. INTRODUCTION

This analysis is a continuation of the feasibility study of direct disposal of dual purpose canisters (DPCs) documented in detail in *Preliminary System Analysis of Direct Dual Purpose Canister Disposal* [Ref. 3], and summarized in *Preliminary Report on Dual-Purpose Canister Disposal Alternatives (FY13)* [Ref. 1]. The previous study assumed that the reactor sites will continue to load DPCs according to their current practice until all the fuel is transferred to dry storage. It was assumed that an interim storage facility (ISF) will start full-scale operations in 2025 and will be used as the surface decay storage facility for DPCs. It was assumed that a repository will start operations in 2048. The ISF and the repository starting dates were based on the goals set forth in the DOE *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* [Ref. 6]. Five emplacement thermal power limits were considered: 4 kW; 6 kW; 8 kW; 10 kW; and 12 kW.

The current study assumed three different starting dates for a repository: 2036 (an early start); 2048 (the planned start); and 2060 (a late start). Three emplacement thermal power limits were considered: 6 kW; 10 kW; and 18 kW. Two fuel loading scenarios were considered. The first scenario called "DPCs only" uses the same assumption as in the previous study. In this scenario the reactor sites continue to load DPCs according to their current practice until all the fuel is transferred to dry storage. The second scenario called "DPCs and STADs" assumes that the reactor sites will start loading small standard transportation, aging, and disposal canisters (STADs) (4PWR/9BWR) five years before the repository starting date.

The previous study concluded that the DPC-only scenarios result in the additional storage capacity required at the ISF and additional repository emplacement time (extended decay storage) when compared to the reference case in which the fuel is re-packaged [Ref. 1]. The additional storage capacity and emplacement time lead to the additional costs: capital cost to deploy the additional ISF storage facility and the cost to continue ISF operations for an additional period of time. The current study investigates how these conclusions may be affected by the use of STADs, early or late start of the repository, and the larger (18 kW) emplacement thermal power limit. The current study also addresses an additional factor that may affect the feasibility of the DPC disposal, which is the fuel age at the emplacement.

2. LOGISTIC SIMULATION SETUP

The major parameters addressed by the system-level analysis are the repository starting date; the emplacement power limit; and the fuel loading scenario. The rationale for selecting these parameter values are discussed below.

The repository starting dates selected for the analysis are: 2036; 2048; and 2060. The 2048 date is from the DOE Strategy [Ref. 6]. The 2036 date could represent an early start, which might be possible if an aggressive program is implemented. The 2060 date represents a late start representing unplanned difficulty with implementation.

The considered emplacement thermal power limits are: 6 kW; 10 kW; and 18 kW. The 6 kW limit is for sedimentary media, which requires long ventilation-cooling time. The duration of aging after emplacement in the repository could be 150 years or more as demonstrated in Ref. 3. The 10 kW limit is an approximate limit for packages of any size emplaced in salt assuming 200°C peak salt temperature limit. The 18 kW limit was used for Yucca Mountain and was based on off-normal conditions during preclosure handling. Consequently, this thermal limit requires a concept similar to Yucca Mountain, such as an open emplacement mode in unsaturated unbackfilled hard rock.

As the repository siting proceeds and the disposal requirements become known, fuel loading practices may change. To evaluate these changes two fuel loading scenarios were considered. In the first scenario the fuel is loaded in DPCs based on the current practice. In the second scenario the fuel is loaded into the existing DPCs until 5 years from the repository opening date. After that all the sites begin loading fuel into the small STADs (4PWR/9BWR). Using small STADs should provide a bounding estimate of the benefits related to the use of STADs. The benefits (if any) from implementing medium and large STADs should be between the DPCs-only scenario and DPCs and small STADs scenario.

The assumption regarding the STAD implementation time (5 years prior to the repository opening) is bounding as well. It is likely that the implementation time will be 10 years prior to the repository opening. The standardization task plan estimates that during these 10 years there would be 1 year to complete the repository LA design, 4 years repository licensing and 5 years repository construction.

The combinations of the repository starting dates, emplacement thermal power limits, and fuel loading scenarios result in 18 different alternatives (Table 1). These alternatives were evaluated using CALVIN portion of the Transportation Storage Logistics simulator (TSL-CALVIN) [Ref. 4].

Table 1. Description of Alternatives Considered in the System-Level Analysis.

Alternative	Repository Starting Date	Thermal Power Limit (kW)	Fuel Loading Scenario
Alternative 1	2036	6	DPCs-Only
Alternative 2	2036	6	DPCs and STADs
Alternative 3	2036	10	DPCs-Only
Alternative 4	2036	10	DPCs and STADs
Alternative 5	2036	18	DPCs-Only
Alternative 6	2036	18	DPCs and STADs
Alternative 7	2048	6	DPCs-Only
Alternative 8	2048	6	DPCs and STADs
Alternative 9	2048	10	DPCs-Only
Alternative 10	2048	10	DPCs and STADs
Alternative 11	2048	18	DPCs-Only
Alternative 12	2048	18	DPCs and STADs
Alternative 13	2060	6	DPCs-Only
Alternative 14	2060	6	DPCs and STADs
Alternative 15	2060	10	DPCs-Only
Alternative 16	2060	10	DPCs and STADs
Alternative 17	2060	18	DPCs-Only
Alternative 18	2060	18	DPCs and STADs

The other assumptions used in this analysis are described below.

The total commercial used nuclear fuel (UNF) inventory considered in the analysis is 139,000 MTU. This total inventory consists of the existing inventory and the projected inventory through 2055. The projected inventory is calculated using a number of assumptions including the license termination dates, power uprates, new builds and others. The current projection in the CALVIN database was used. However, this current projection may change in the future if one or more of the above assumptions are modified.

It was assumed that the UNF is transported from the reactor sites to the ISF in DPCs (welded dry storage canisters and bolted dry storage casks) or small STADs. The current site-specific dry storage practice used in this analysis is described in Appendix A of *Used Fuel Management System Architecture Evaluation, Fiscal Year 2012* [Ref. 5].

It was assumed that all DPCs are transportable and disposable. This assumption was used because of two main reasons. First, it simplifies the logistics calculations. Second, an additional analysis is needed to evaluate the disposability of DPCs. There are currently at least 26 different DPC designs. Some of them are welded-sealed DPCs and some of them are bolted DPCs. Not all designs have been licensed for transport. The results of this evaluation will provide an input for the next iteration of the direct disposal of DPCs study.

It was assumed that the ISF begins its operations in 2025. The DPCs and STADs are transported to the ISF where they are stored until their thermal power meets the repository emplacement power thermal limit in consideration. Two ISF/repository acceptance rates were considered – 3,000 MTU/year and 4,500 MTU/year. These rates set the maximum limits for the waste acceptance. The actual waste acceptance rates might be below these limits as discussed in Sections 3.2.1 and 3.2.2.

The reference repackaging case assumed that all UNF will be transported to the ISF, repackaged, and transported to the repository. The ISF acceptance rate was set equal to the repository acceptance rate. Under these assumptions, the ISF capacity reaches its maximum value at the repository starting date and then maintains this capacity until insufficient UNF is available from the reactor sites to achieve the specified acceptance rate. From this date the capacity decreases linearly until all UNF is transported to the repository. Figure 1 shows the ISF capacity versus time for the different repository starting dates and acceptance rates. Note that the time from the repository opening date until the date when all UNF is transported to the repository is 47 years for all repository starting dates with the repository acceptance rate of 3,000 MTU/year and 31 years for all repository starting dates with the repository acceptance rate 4,500 MTU/year. The maximum ISF capacities and the operational times in the reference repackaging scenario are used to calculate the additional ISF capacity and additional emplacement time due to extended storage for each of the direct disposal of DPCs/STADs alternatives listed in Table 1.

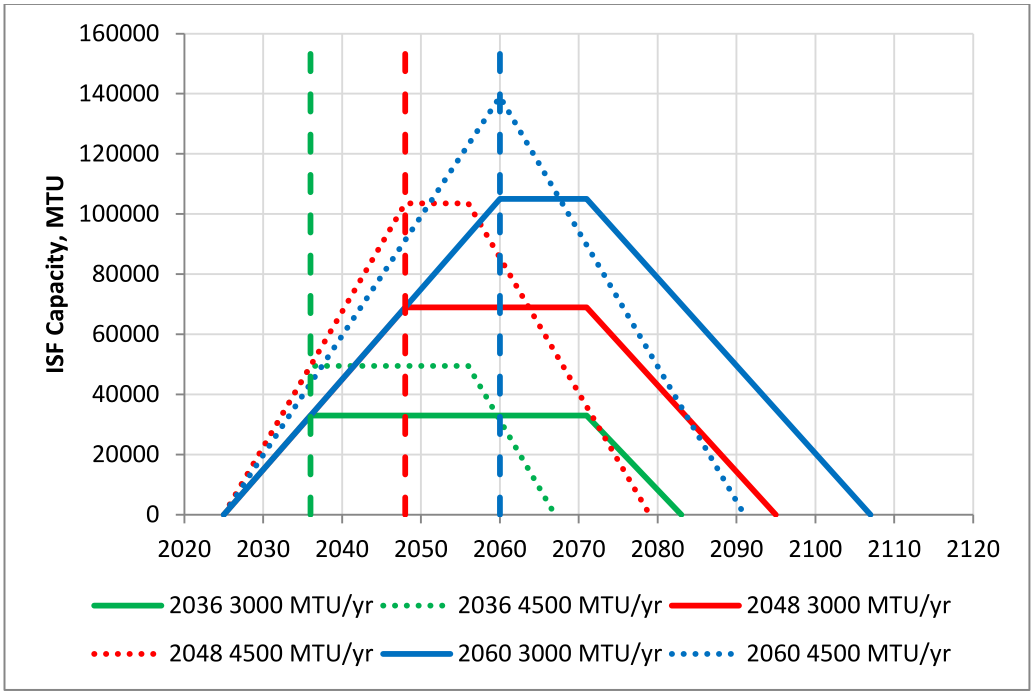
The CALVIN module of the Transportation Storage Logistics simulator (TSL-CALVIN) [Ref. 4] was used to perform the logistic calculations. The approach similar to the one described in Ref. 3 was used.

First, CALVIN was used to determine the amount of UNF in DPCs that is available each year for disposal and how this amount is affected by the repository starting date, thermal power limit, and use of STADs. Note that the annual amount of UNF available for disposal does not depend on either the ISF or the repository acceptance rate.

Second, two ISF/repository acceptance rates (3,000 and 4,500 MTU/year) were considered to determine the actual repository acceptance rate during the period of operations, maximum ISF capacity, and ISF operational time for the different DPCs/STADs alternatives. The maximum ISF capacity and operational time were used to calculate the additional storage capacity and emplacement time compared to the reference repackaging case.

At the final step the fuel age at emplacement was considered assuming the repository acceptance rate of 3,000 MTU/year.

The results of the simulations are presented in Section 3.



NOTE: The vertical dashed lines show three different repository starting dates.

Figure 1. ISF Capacity as a Function of the Repository Starting Date and Acceptance Rate for the Reference Repackaging Cases.

3. RESULTS OF THE ANALYSIS

This section presents the results of the logistic simulations that considered the18 alternatives described in Table 1. The availability of waste for disposal is discussed in Section 3.1. The repository acceptance rates are discussed in Section 3.2. The comparison of the 18 alternatives with the reference repackaging scenario is provided in Section 3.3. The fuel age at emplacement is discussed in Section 3.4.

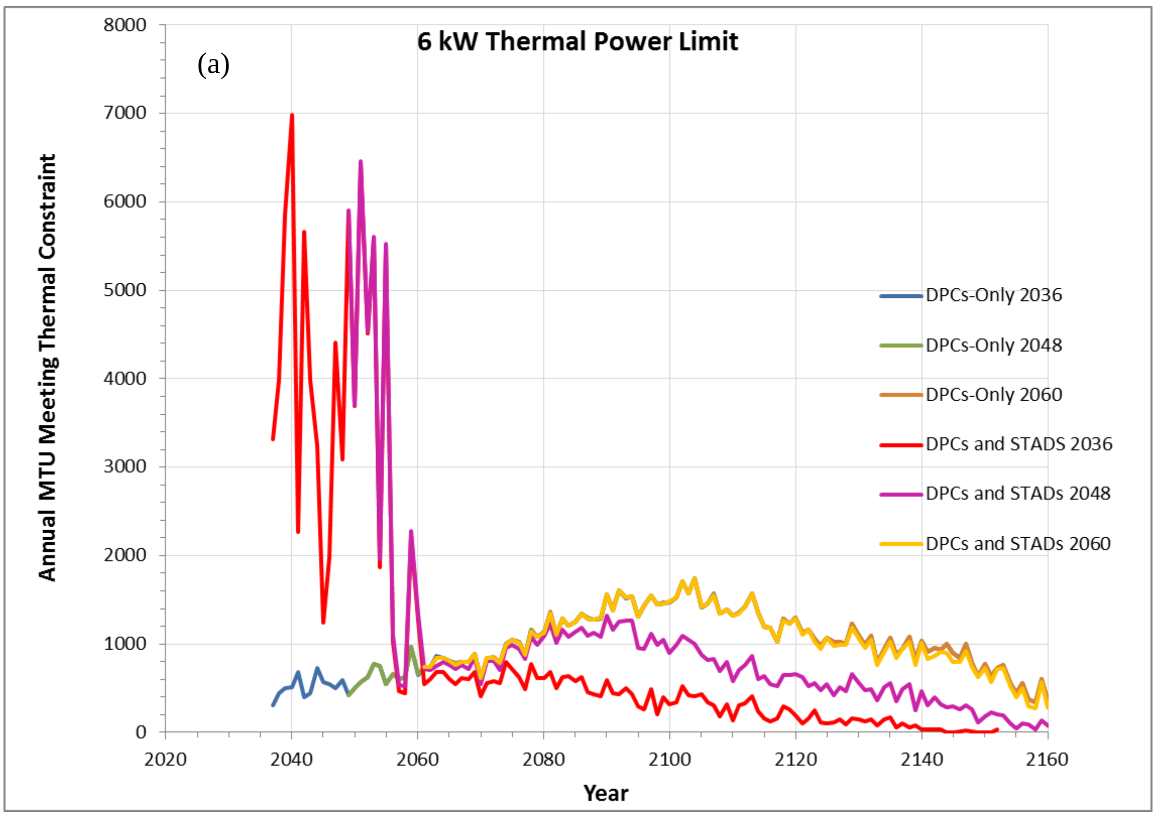
3.1 DPCs and STADs Availability

The annual and cumulative amounts of UNF in DPCs only or UNF in DPCs and small STADs that are cool enough to meet the repository emplacement thermal power limits are shown in Figures 2a and 2b (6 kW thermal power limit), Figures 3a and 3b (10 kW thermal power limit), and Figures 4a and 4b (18 kW thermal power limit) for the different repository opening dates – 2036, 2048, and 2060. The dashed vertical lines show the time of completion of the corresponding repackaging scenario for the 3,000 MTU/year ISF/ repository acceptance rates. Note that Figures 2a, 3a, and 4a do not show the waste available prior to the repository opening date. The availability prior to the repository opening date can be found in Figures 2b, 3b, and 4b, which show cumulative waste inventory.

Figures 2 through 4 demonstrate that the thermal power limit is the most important parameter affecting the amount of UNF in DPCs available for emplacement. The year in which 98% of the total inventory can be emplaced is 2162 for the 6 kW thermal limit; 2112 for the 10 kW thermal limit, and 2074 for the 18 kW thermal limit. In the 18 kW alternatives, the time required to disposed of the DPCs is the same as in the corresponding repackaging cases for both 3,000 and 4,500 MTU/year ISF/repository acceptance rates.

For a specified thermal power limit, the availability of UNF in DPCs-only alternatives is not sensitive to the repository starting dates – the lowermost curve in Figures 2 through 4 represents the three repository starting dates. However, the repository starting date affects how much of the UNF in the DPC-only scenario can be disposed of at the repository starting date, compared to the corresponding repackaging cases. For example, if the repository starting date is 2036 and the thermal power limit is 6 kW, by the time the repackaging is completed (2083) only 36% of the total UNF inventory is cool enough to be emplaced. If the repository starting date is 2060, by the time the repackaging is completed 62% of the total UNF inventory is cool enough to be emplaced under the same thermal power limit constraint.

The availability of UNF in DPCs and small STADs scenarios is significantly affected by the time the STADs are implemented, which in this analysis was assumed to be 5 years before the repository starting date. More UNF in DPCs and small STADs is available when the STADs are implemented in 2031 (repository in 2036) compared to later repository starting dates. In the case of the late implementation in 2055 (repository in (2060) the availability of UNF in DPCs and small STADs is only slightly higher than in the DPCs-only scenarios. This conclusion is true for all the thermal power limits. However, the most significant impact from use of the small STADs is for the 6 kW thermal power limit.



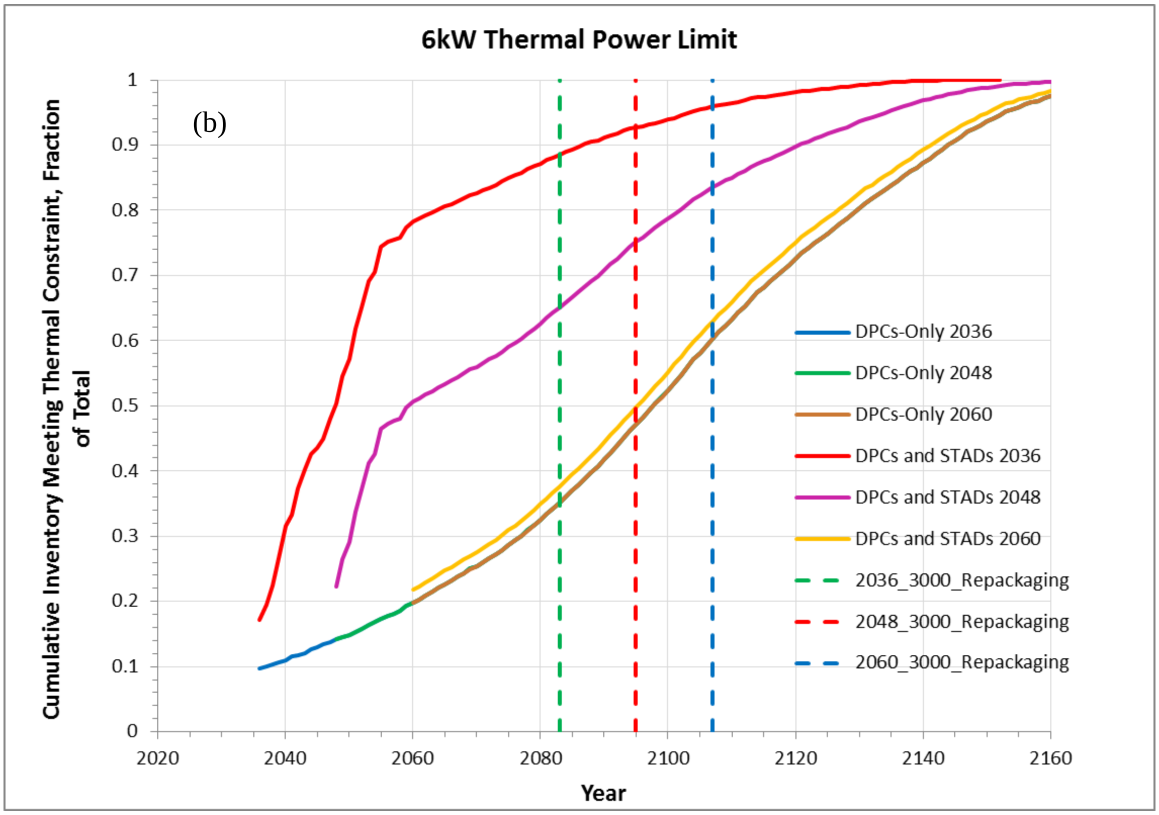
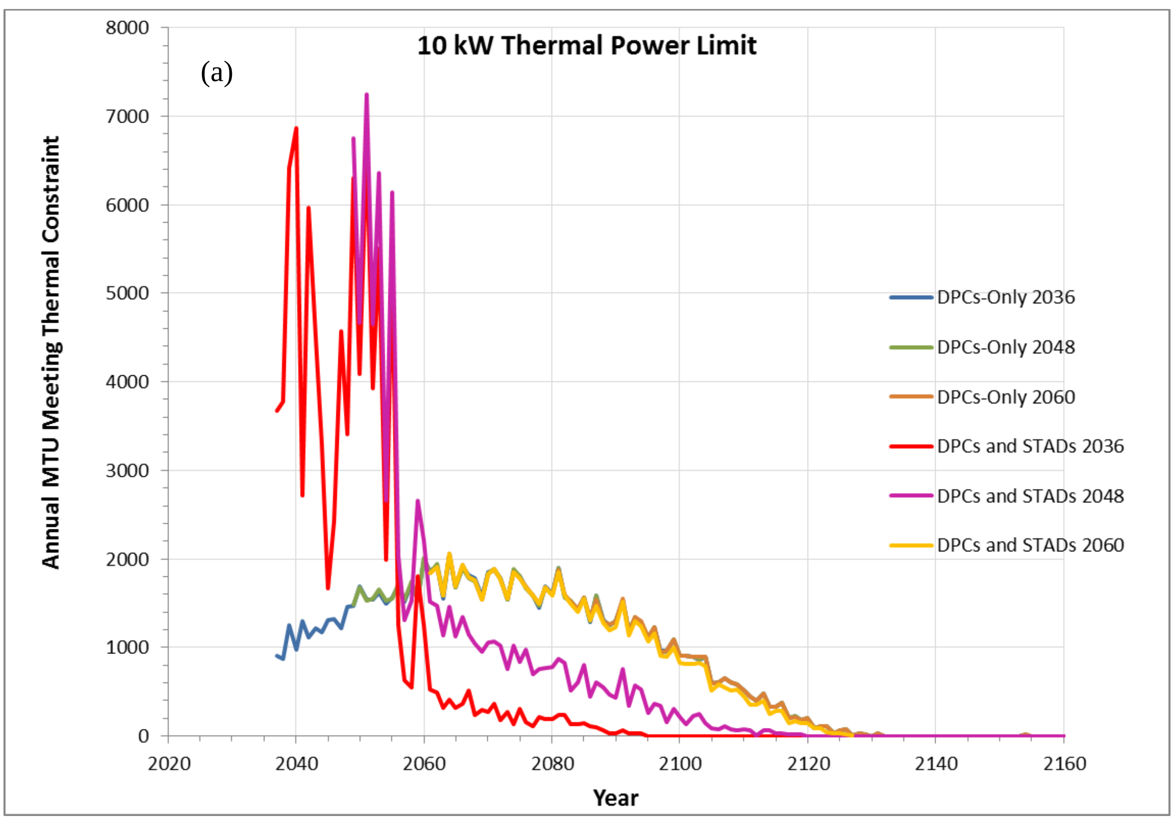


Figure 2. Annual (a) and Cumulative (b) Inventory Available for Disposal in a Repository with 6 kW Thermal Constraint.



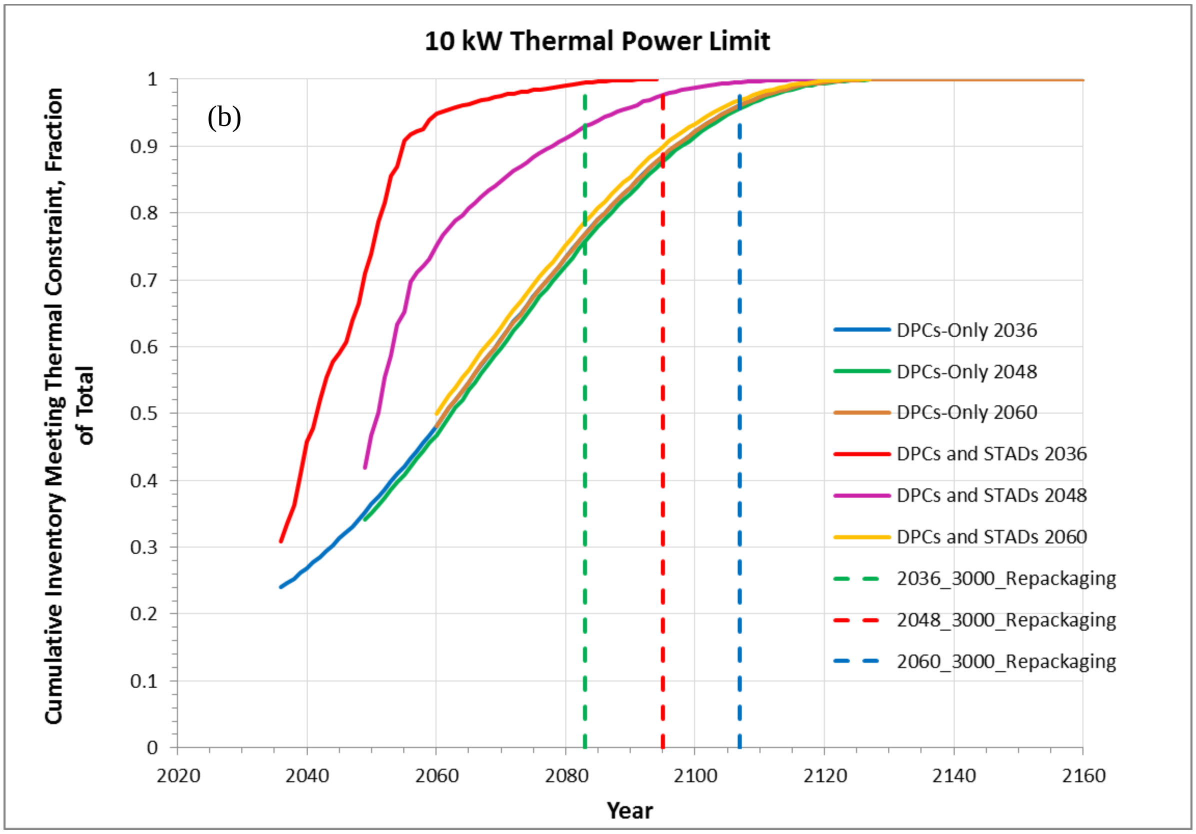
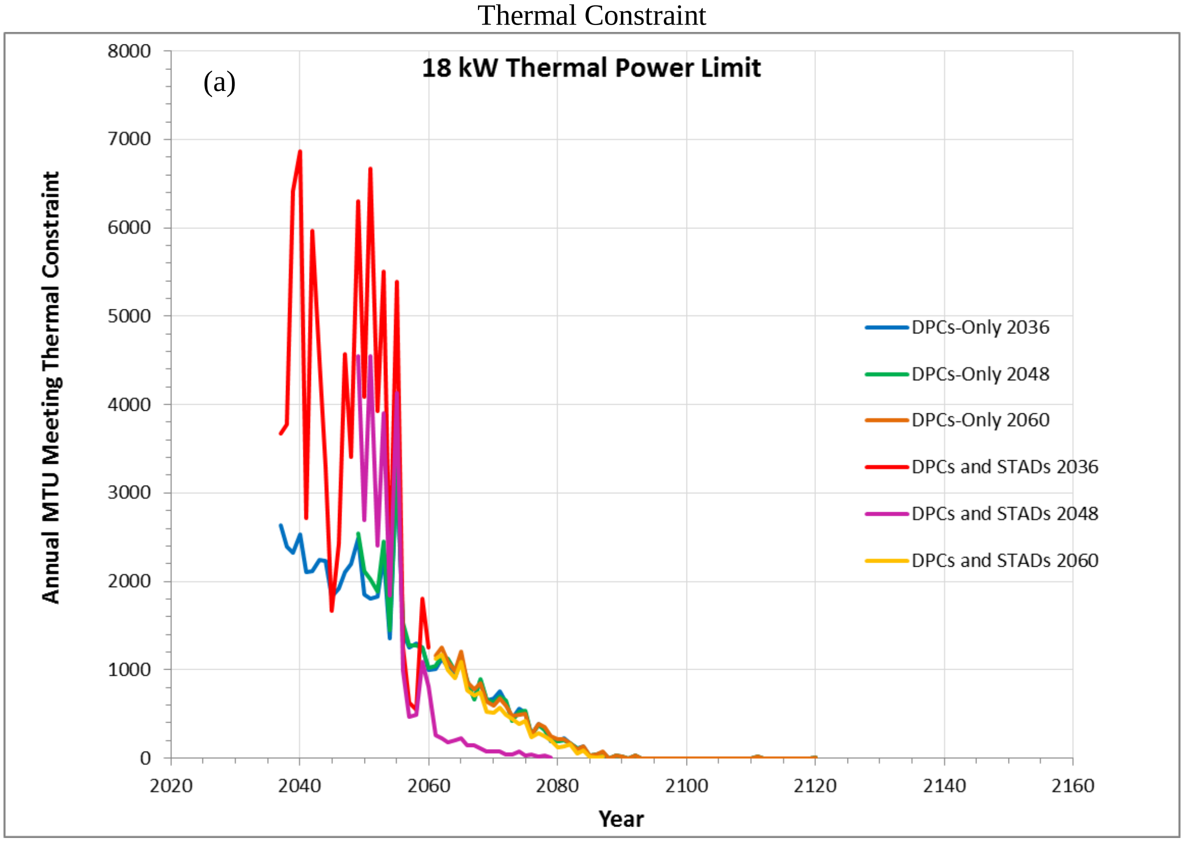


Figure 3. Annual (a) and Cumulative (b) Inventory Available for Disposal in a Repository with 10 kW Thermal Constraint



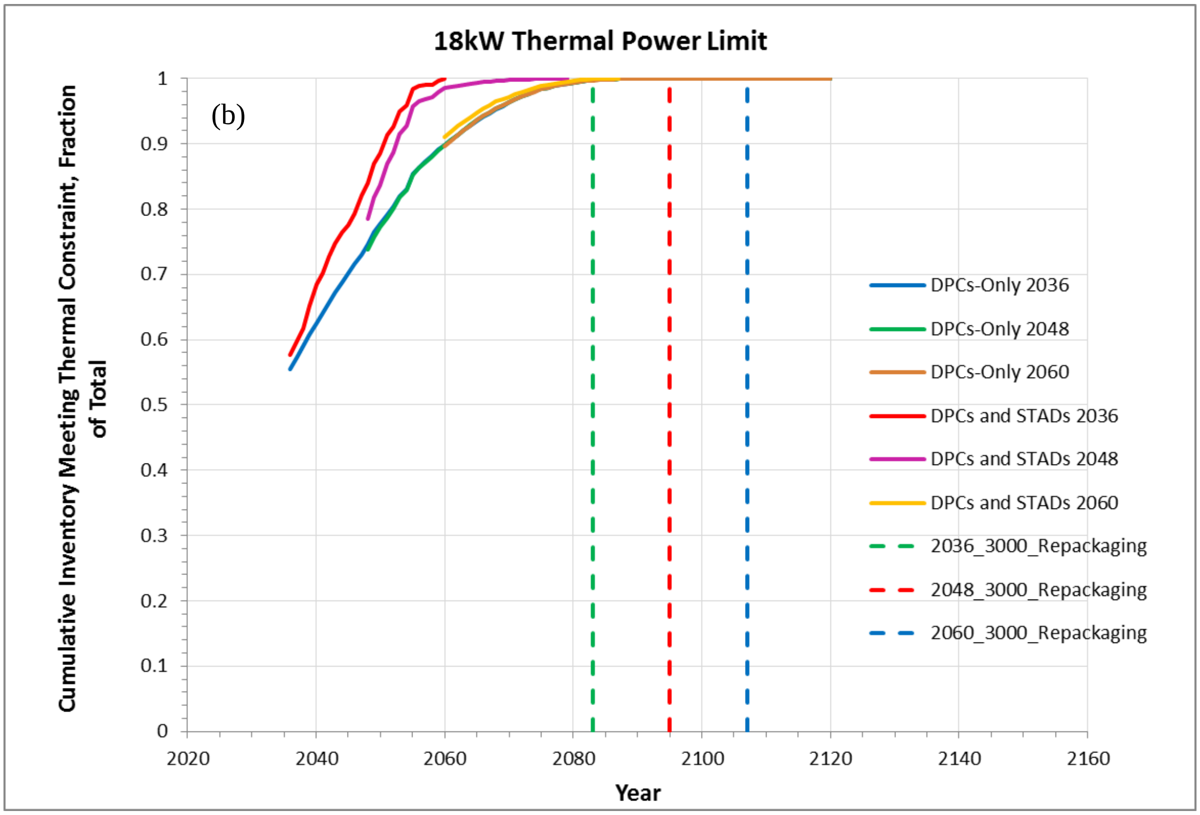


Figure 4. Annual (a) and Cumulative (b) Inventory Available for Disposal in a Repository with 18 kW Thermal Constraint.

3.2 Repository Acceptance

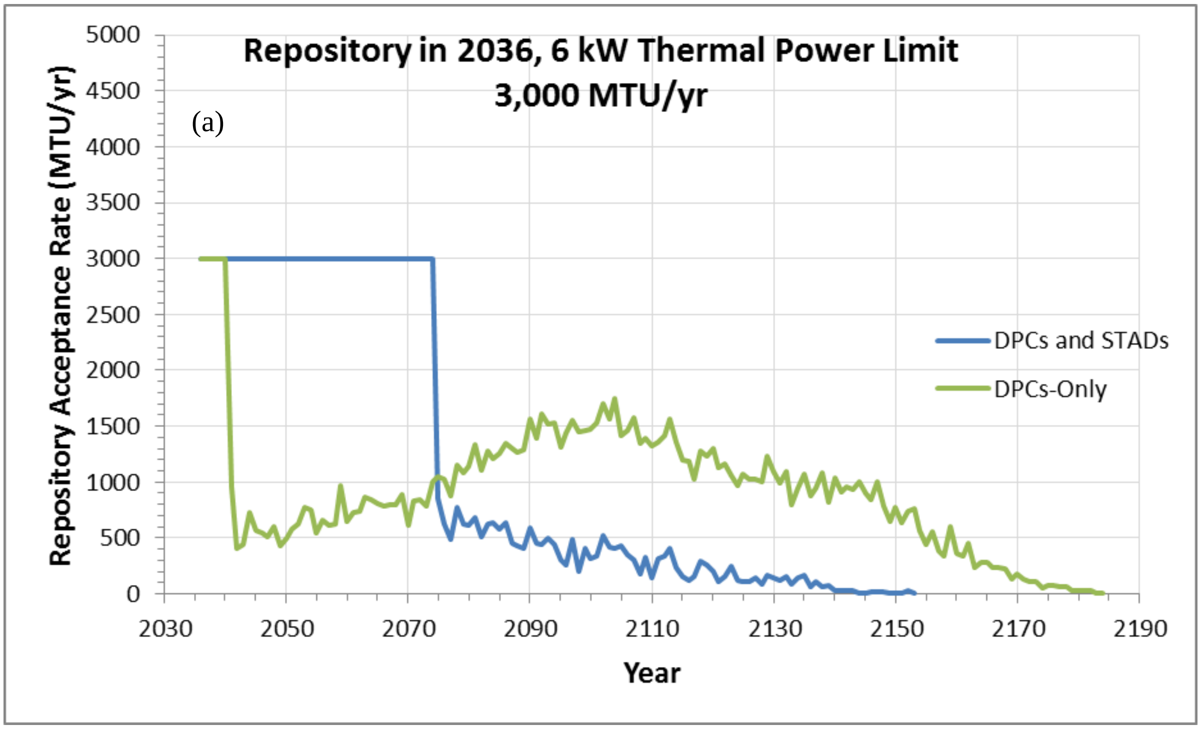
The forecast repository DPC acceptance rates for each emplacement power thermal limit and each repository starting date are discussed in Section 3.2.1 (maximum annual acceptance rates of 3,000 MTU/year) and Section 3.2.2 (maximum annual acceptance rates of 4,500 MTU/year).

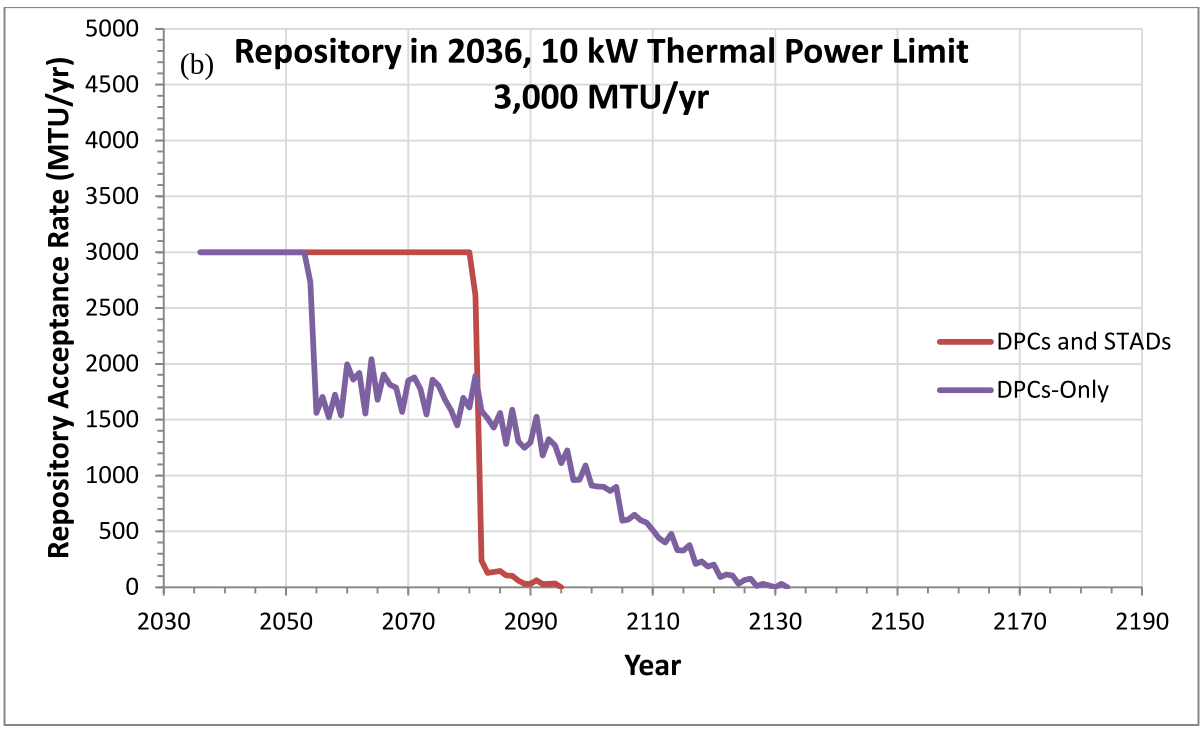
3.2.1 Repository Acceptance Rate of 3,000 MTU per Year

The actual repository acceptance rates calculated assuming the maximum repository acceptance rate of 3,000 MTU/year are shown in Figure 5(a, b, and c) for the repository in 2036, Figure 6 (a, b, and c) for the repository in 2048, and Figure 7(a, b, and c) for the repository in 2060.

The acceptance rates with the emplacement thermal limit of 18 kW (Figures 5c, 6c, and 7c) are not sensitive to either repository starting date or the fuel loading scenario. The repository acceptance rate can be maintained at 3,000 MTU/year during most of the operational period in all these alternatives.

The alternatives with 6 kW and 10 kW thermal power limits are impacted by the repository starting date and the fuel loading scenario. Using small STADs during the early (2036) and planned (2048) repository starting date allows for maintaining maximum repository acceptance rates over significantly longer period of time (Figures 5a and 5b and Figures 6a and 6b). Implementing small STADs in the case of late repository start (2060) has no impact on the repository acceptance rate.


Repository in 2036, 6 kW Thermal Power Limit
3,000 MTU/yr
(a)
Repository Acceptance Rate (MTU/yr)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2030
2050
2070
2090
2110
2130
2150
2170
2190
Year
DPCs and STADs
DPCs-Only


Repository in 2036, 10 kW Thermal Power Limit
3,000 MTU/yr
(b)
Repository Acceptance Rate (MTU/yr)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2030
2050
2070
2090
2110
2130
2150
2170
2190
Year
DPCs and STADs
DPCs-Only

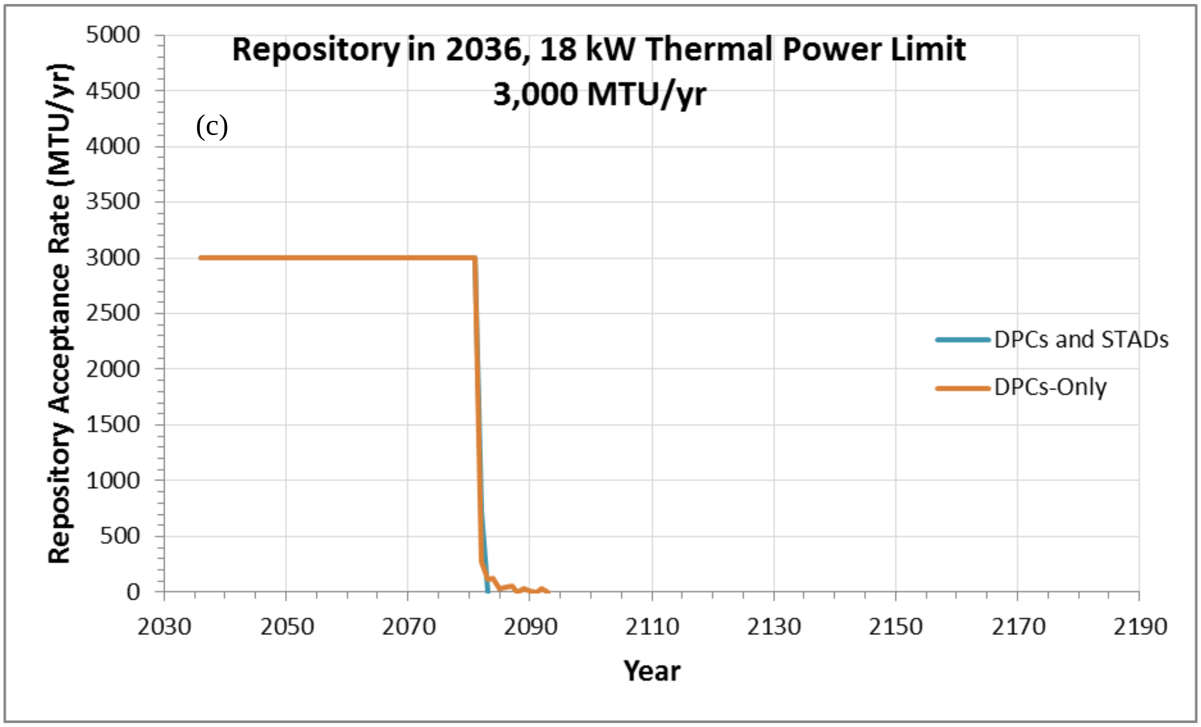
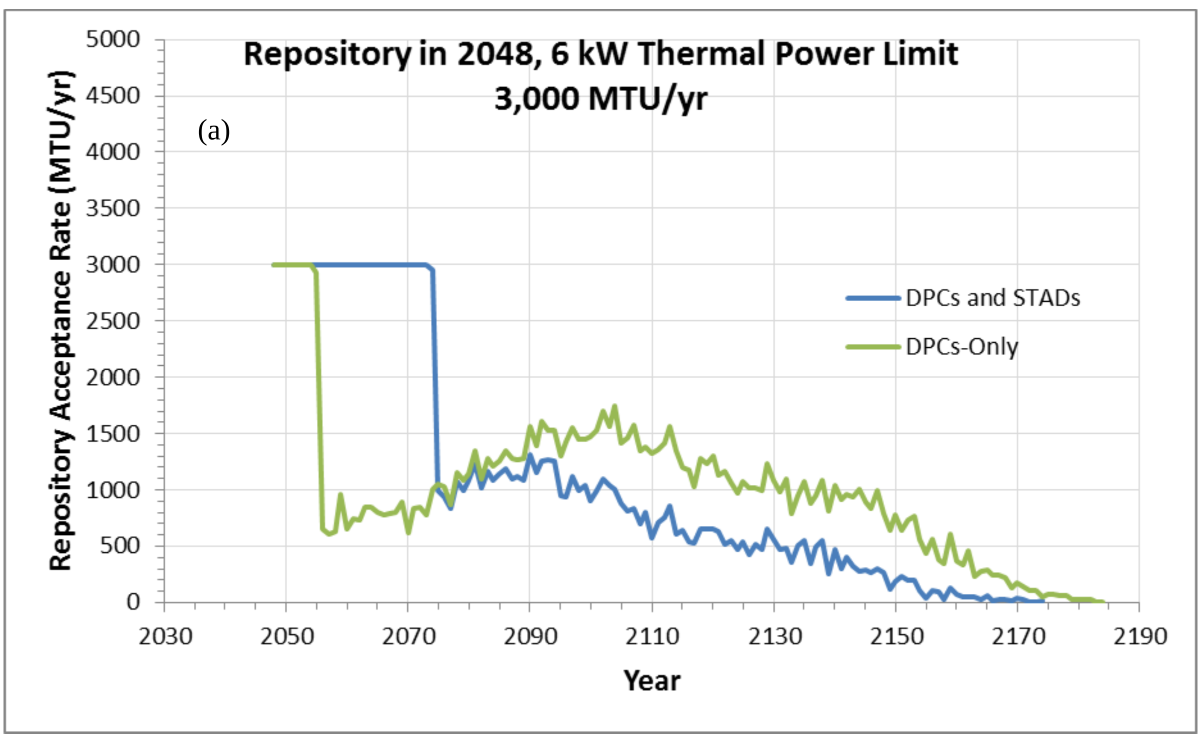
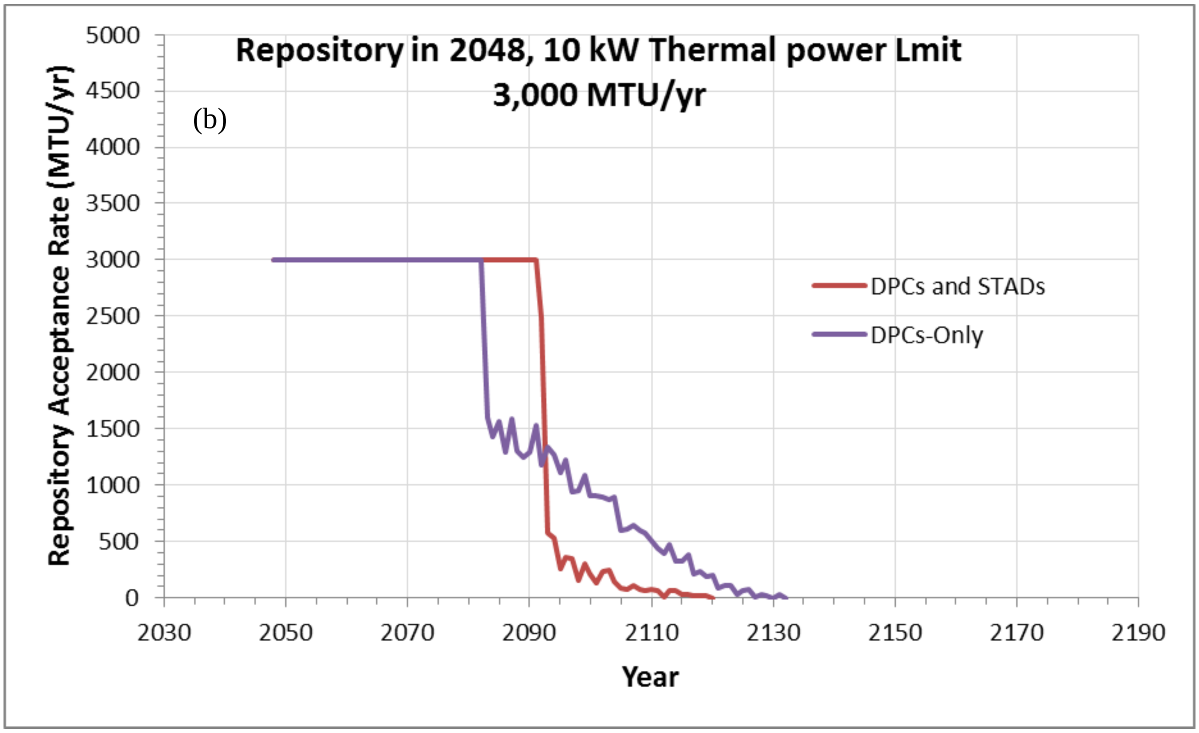


Figure 5. Annual Repository Acceptance for a Repository with (a) 6 kW; (b) 10 kW; and (c) 18 kW Thermal Power Limit, Repository Maximum Acceptance Rate 3,000 MTU/yr and Starting Date in 2036.





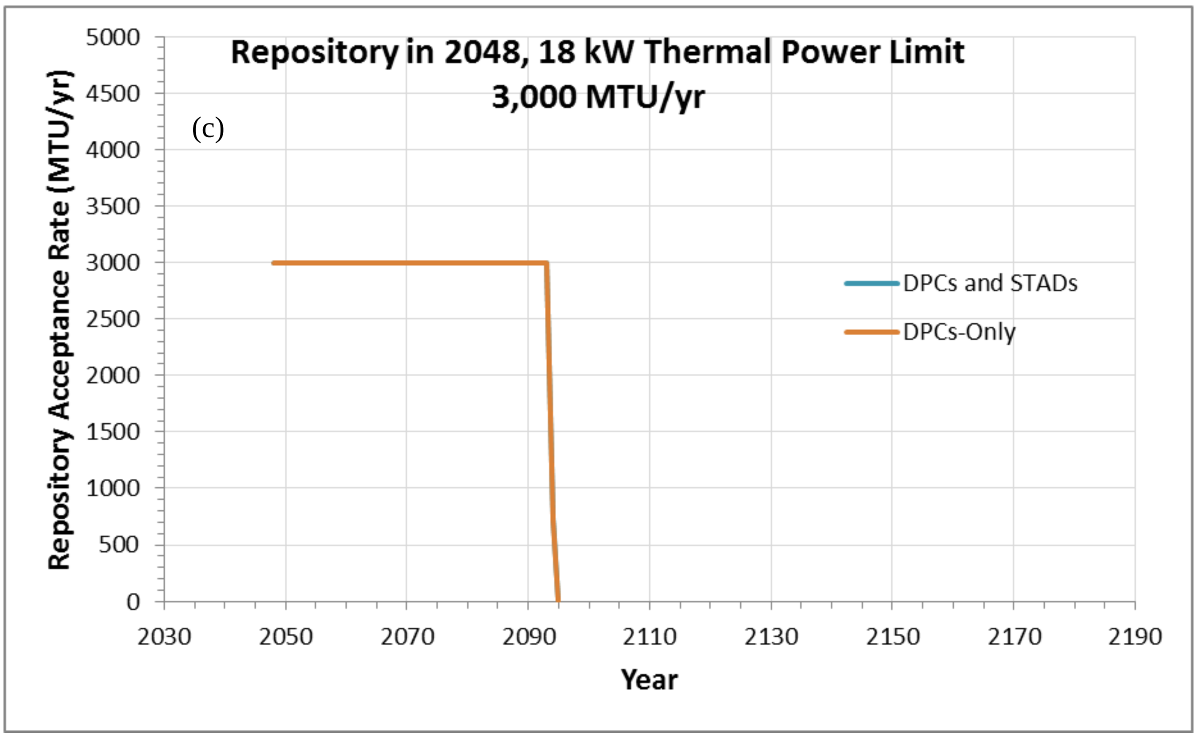
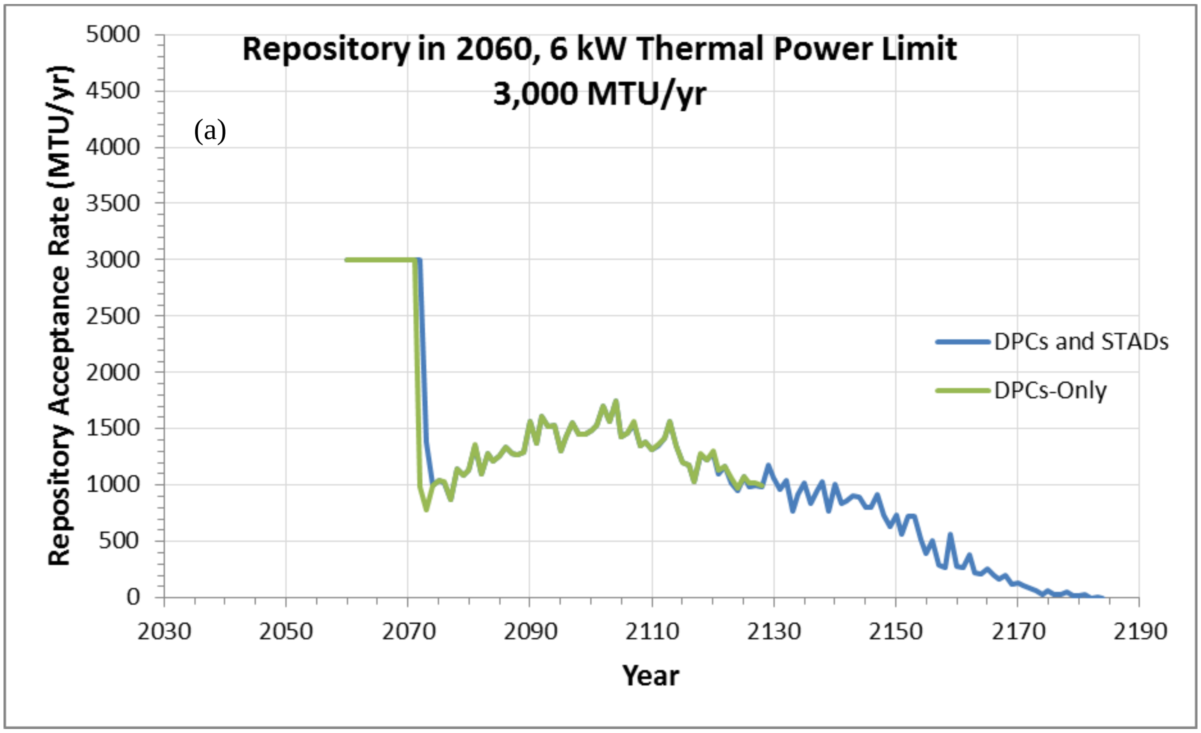
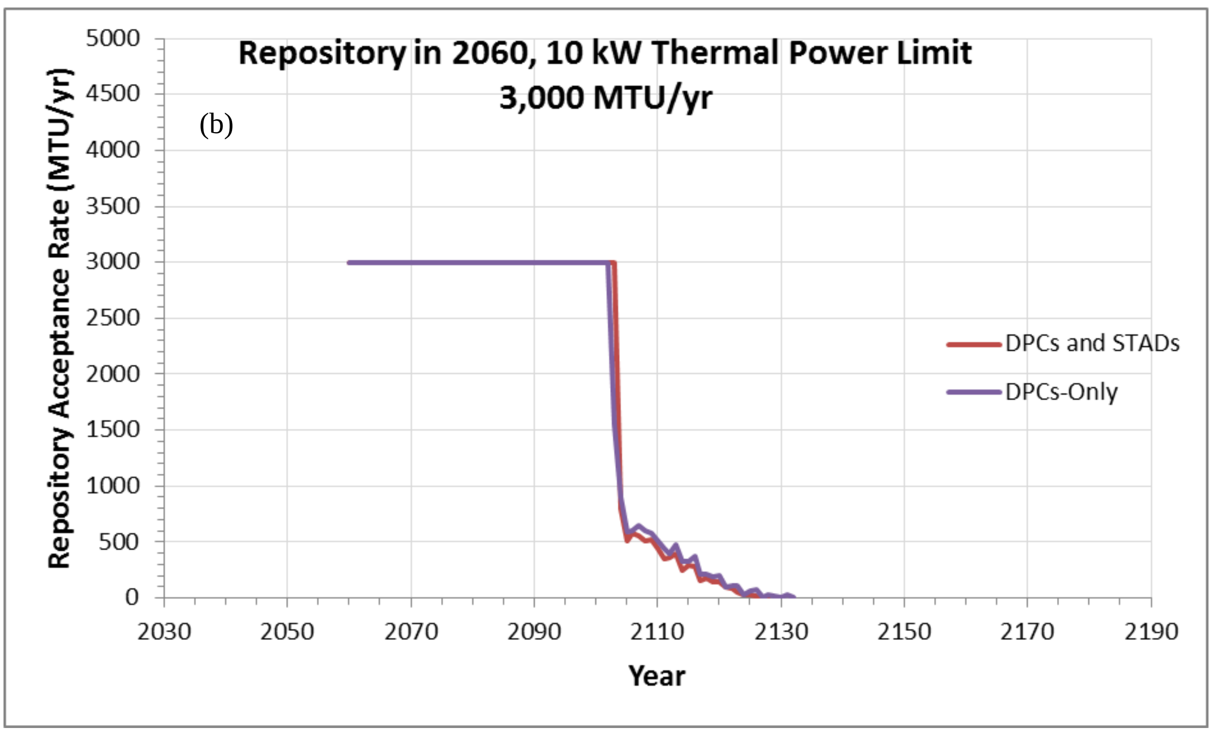


Figure 6. Annual Repository Acceptance for a Repository with (a) 6 kW; (b) 10 kW; and (c) 18 kW Thermal Power Limit, Repository Maximum Acceptance Rate 3,000 MTU/yr and Starting Date in 2048.


Repository in 2060, 6 kW Thermal Power Limit
3,000 MTU/yr
(a)
Repository Acceptance Rate (MTU/yr)
Year
DPCs and STADs
DPCs-Only
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
2030
2050
2070
2090
2110
2130
2150
2170
2190


Repository in 2060, 10 kW Thermal Power Limit
3,000 MTU/yr
(b)
Repository Acceptance Rate (MTU/yr)
Year
DPCs and STADs
DPCs-Only
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
2030
2050
2070
2090
2110
2130
2150
2170
2190

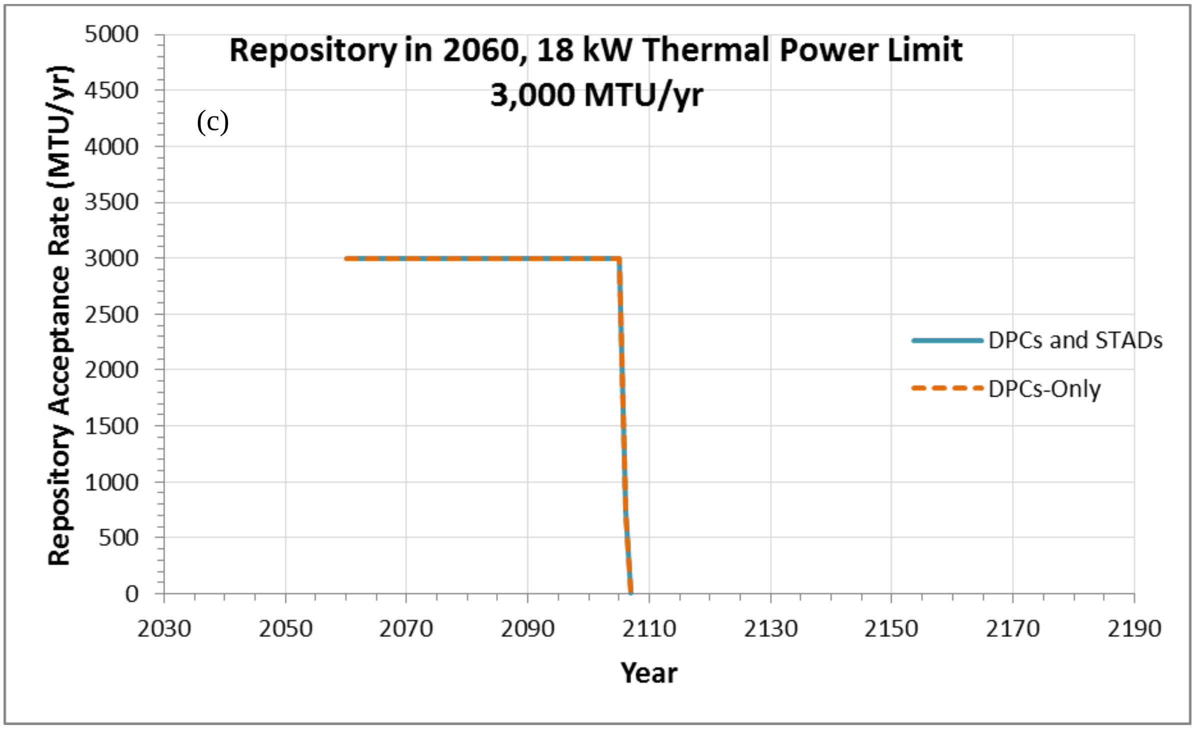


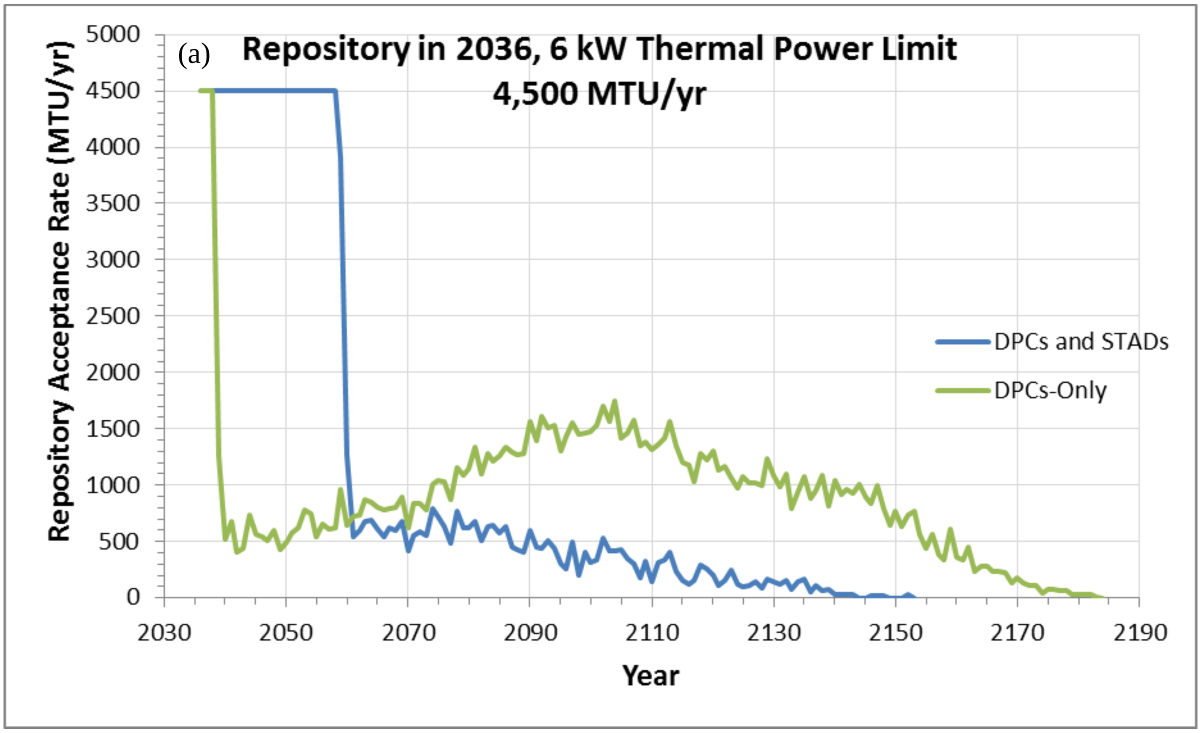
Figure 7. Annual Repository Acceptance for a Repository with (a) 6 kW; (b) 10 kW; and (c) 18 kW Thermal Power Limit, Repository Maximum Acceptance Rate 3,000 MTU/yr and Starting Date in 2060.

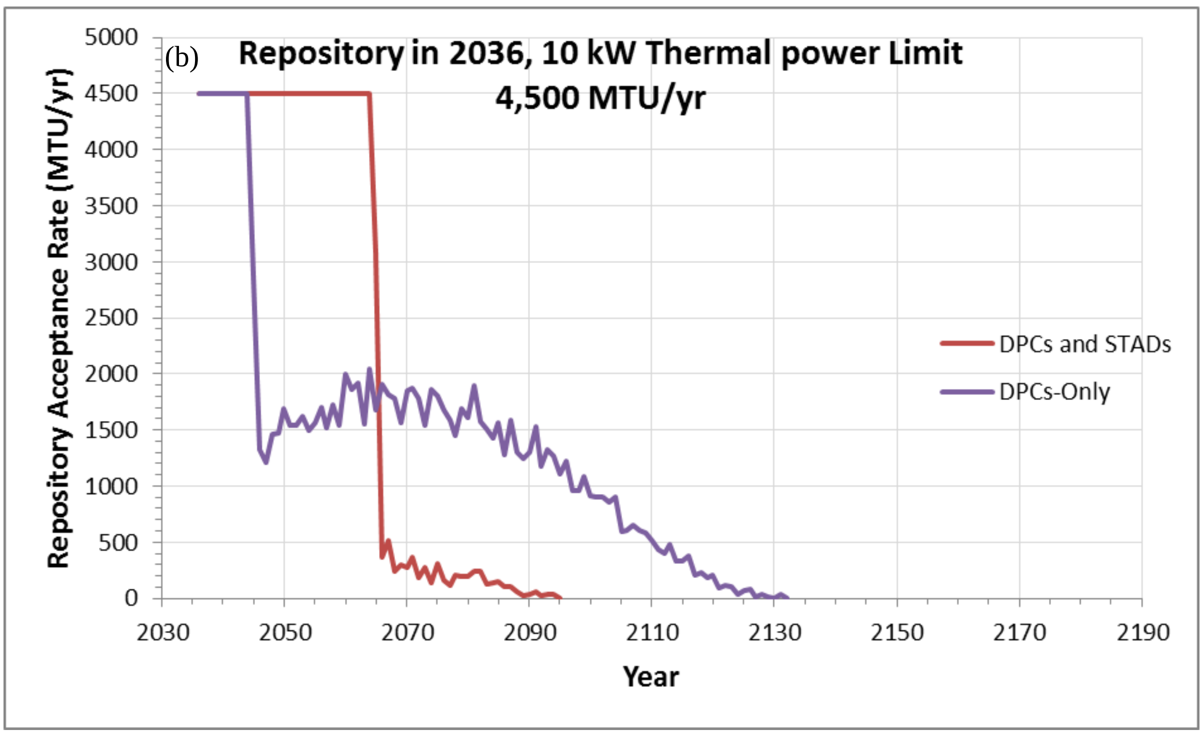
3.2.2 Repository Acceptance Rate of 4,500 MTU per Year

Repository acceptance rates calculated assuming the maximum repository acceptance rate of 4,500 MTU/year are shown in Figure 8(a, b, and c) for the repository in 2036, Figure 9(a, b, and c) for the repository in 2048, and Figure 10(a, b, and c) for the repository in 2060.

The alternatives with the emplacement thermal limit of 18 kW (Figures 8c, 9c, and 10c) are not sensitive to either repository starting date or the fuel loading scenario, except early repository start (2036). The repository acceptance rate can be maintained at 4,500 MTU/year during most of the operational period in all the alternatives with 2048 and 2060 repository starting date and in the DPCs and STADs scenario with 2036 starting date. In the case of the DPCs-only scenario and the 2036 repository starting date the repository acceptance rate drops during the last 10 years of operations.

The alternatives with 6 kW and 10 kW thermal power limits are impacted by the repository starting date and the fuel loading scenario. Implementing small STADs during the early (2036) and planned (2048) repository starting date allows for maintaining maximum repository acceptance rates over significantly longer period of time (Figures 8a and 8b and Figures 9a and 9b). Implementing small STADs in the case of late repository start (2060) has no impact on the repository acceptance rate.


(a)
Repository in 2036, 6 kW Thermal Power Limit
4,500 MTU/yr
Repository Acceptance Rate (MTU/yr)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2030
2050
2070
2090
2110
2130
2150
2170
2190
Year
DPCs and STADs
DPCs-Only


(b)
Repository in 2036, 10 kW Thermal power Limit
4,500 MTU/yr
Repository Acceptance Rate (MTU/yr)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2030
2050
2070
2090
2110
2130
2150
2170
2190
Year
DPCs and STADs
DPCs-Only

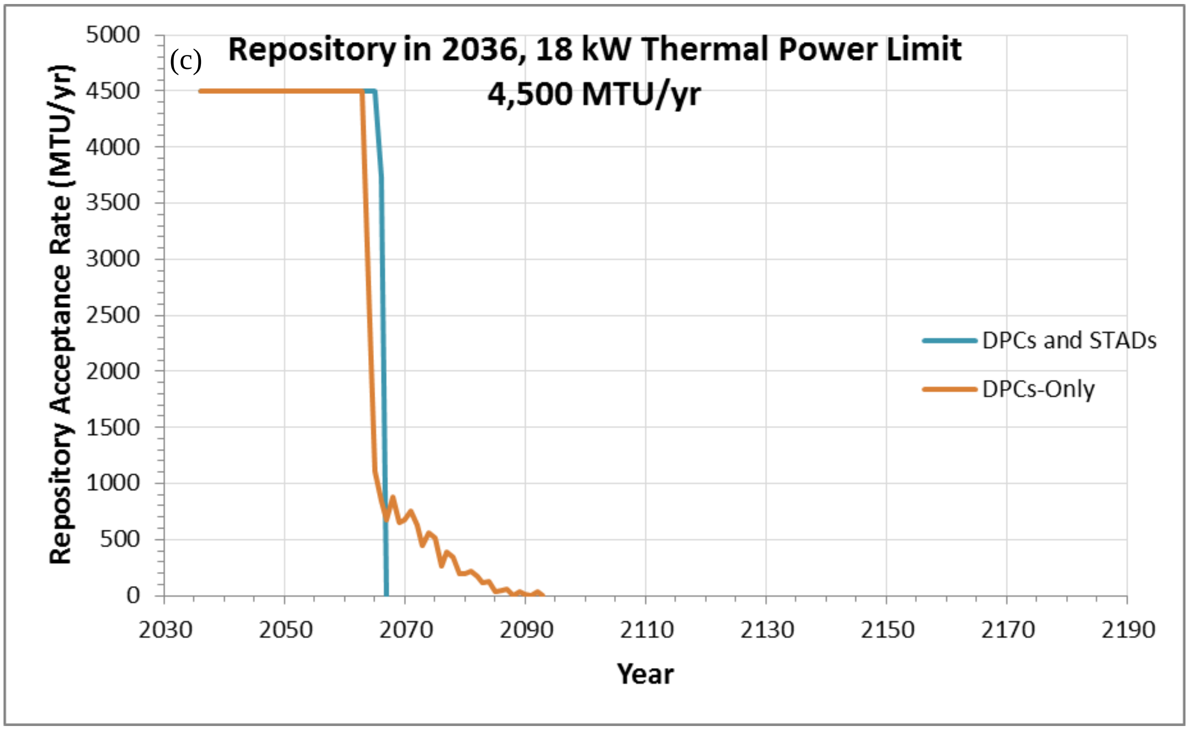
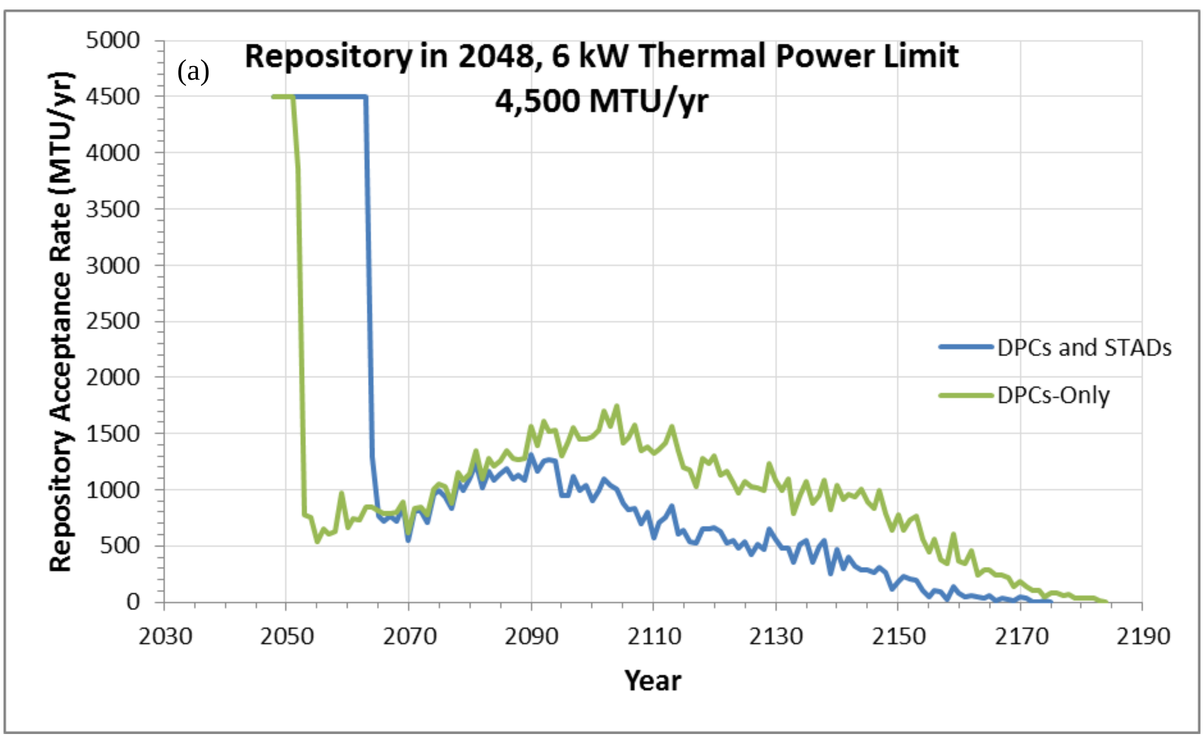


Figure 8. Annual Repository Acceptance for a Repository with (a) 6 kW; (b) 10 kW; and (c) 18 kW Thermal Power Limit, Repository Maximum Acceptance Rate 4,500 MTU/yr and Starting Date in 2036.



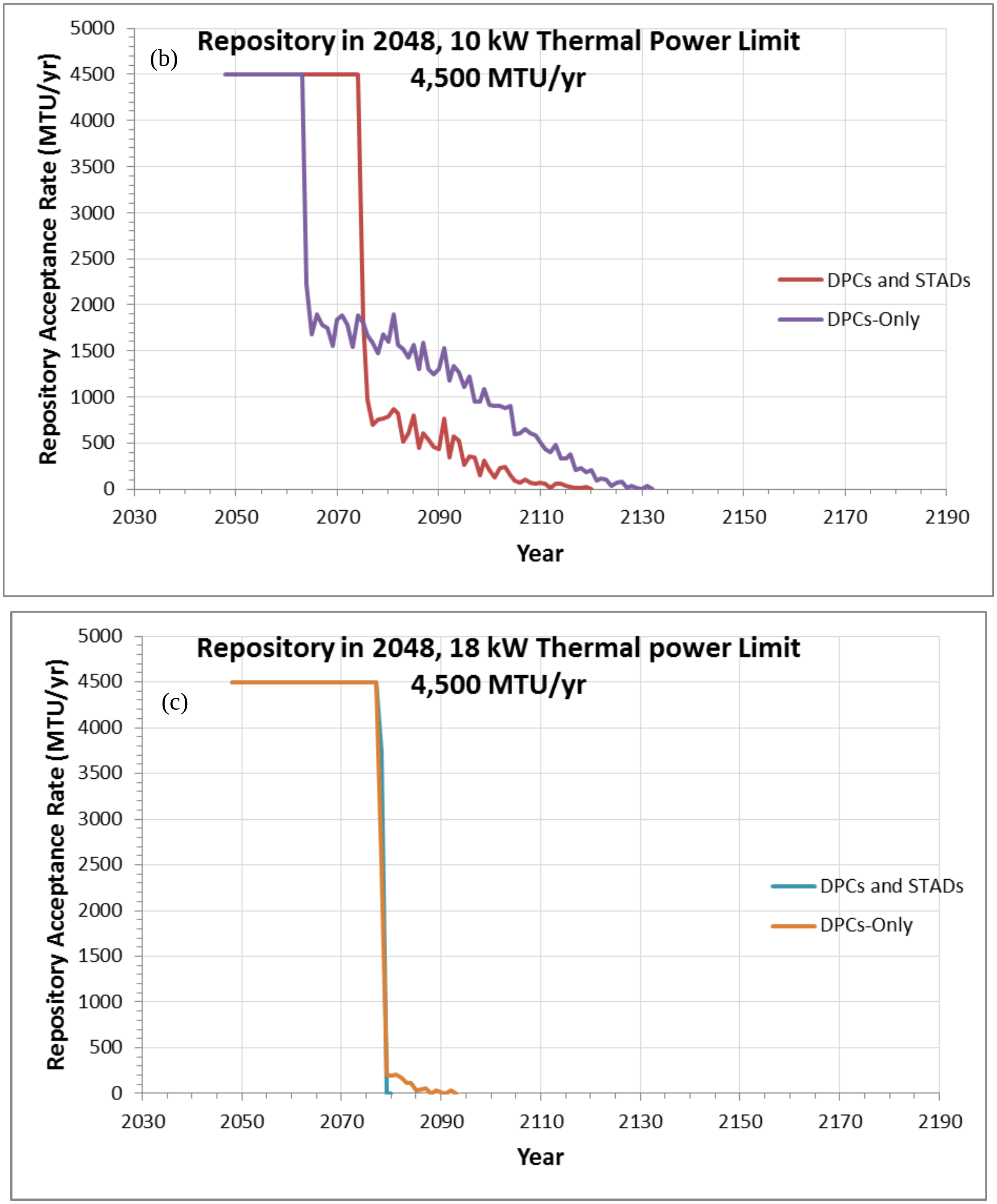
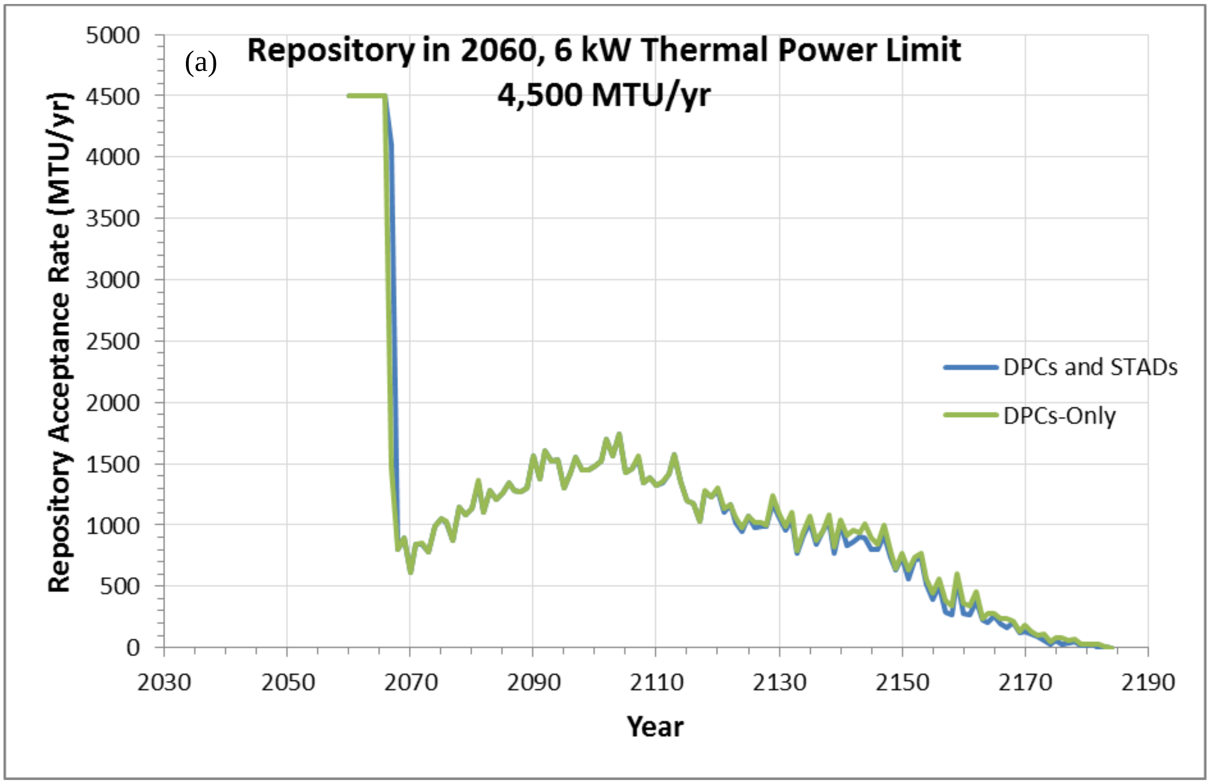
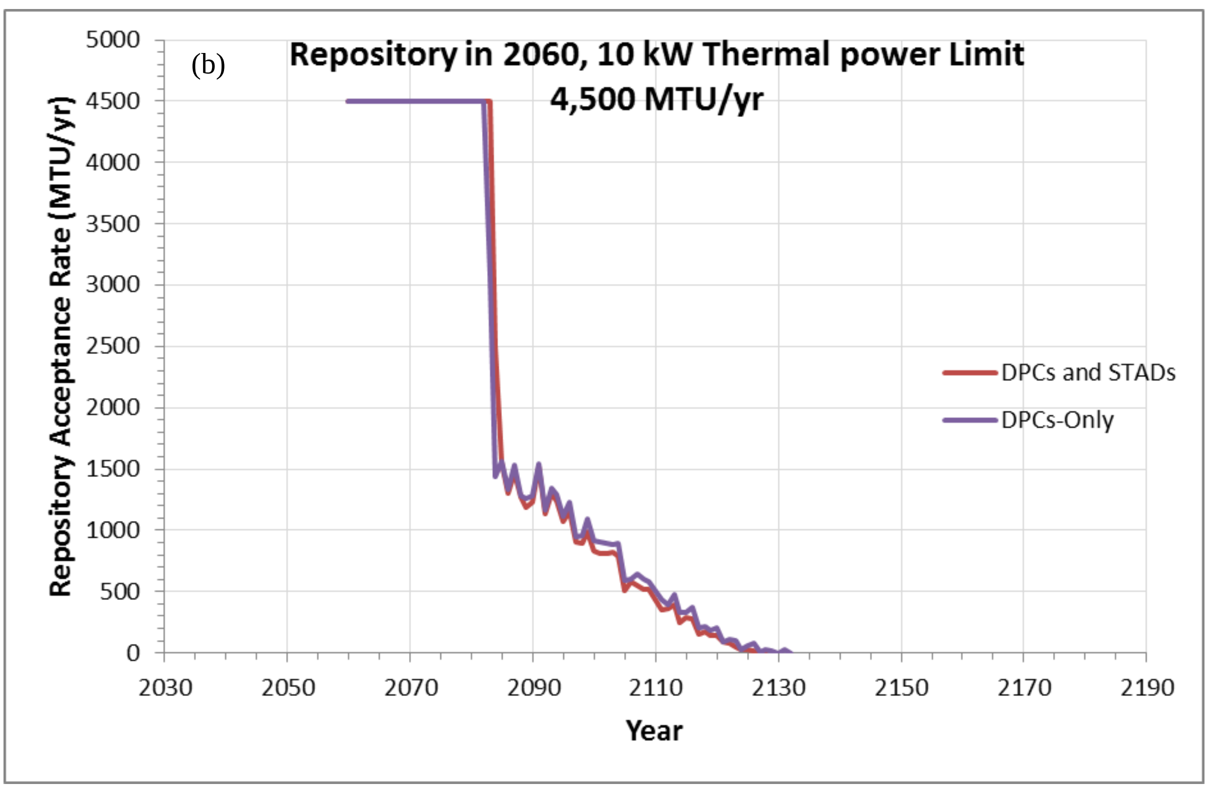


Figure 9. Annual Repository Acceptance for a Repository with (a) 6 kW; (b) 10 kW; and (c) 18 kW Thermal Limit, Repository Maximum Acceptance Rate 4,500 MTU/yr and Starting Date in 2048.


(a)
Repository in 2060, 6 kW Thermal Power Limit
4,500 MTU/yr
Repository Acceptance Rate (MTU/yr)
Year
DPCs and STADs
DPCs-Only
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
2030
2050
2070
2090
2110
2130
2150
2170
2190


(b)
Repository in 2060, 10 kW Thermal power Limit
4,500 MTU/yr
Repository Acceptance Rate (MTU/yr)
Year
DPCs and STADs
DPCs-Only
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
2030
2050
2070
2090
2110
2130
2150
2170
2190

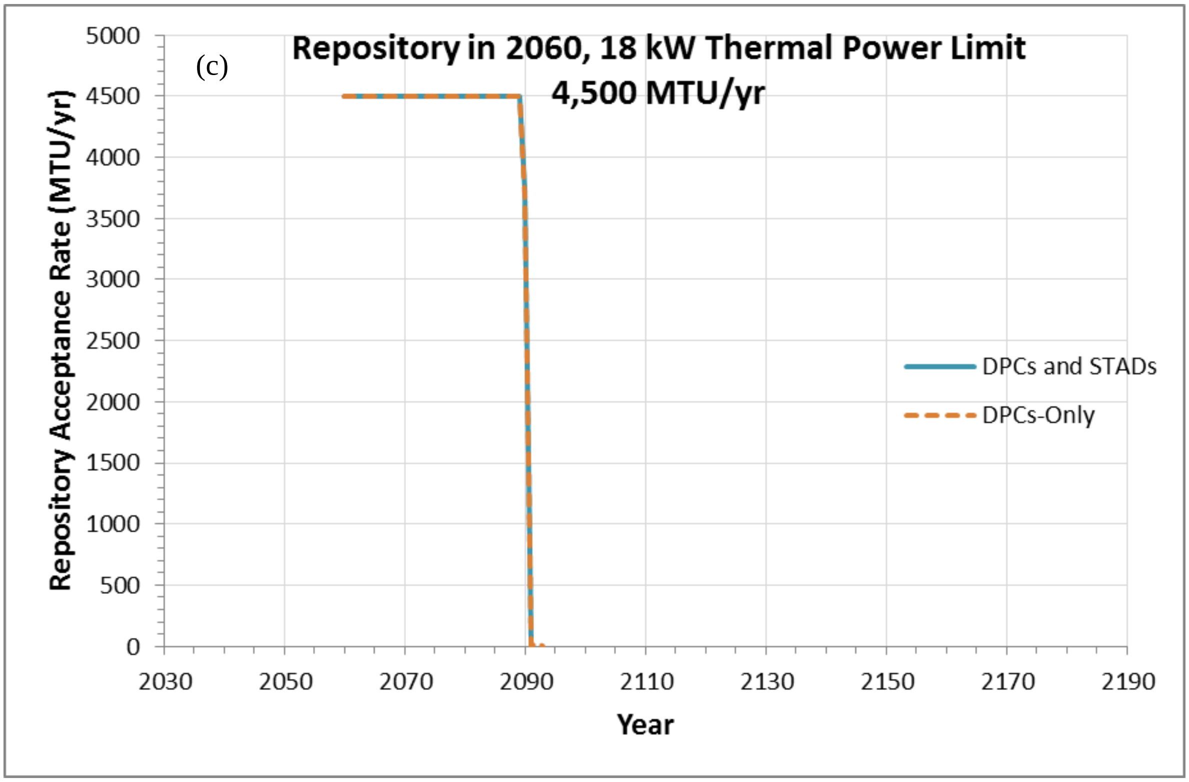


Figure 10. Annual Repository Acceptance for a Repository with (a) 6 kW; (b) 10 kW; and (c) 18 kW Thermal Limit, Repository Maximum Acceptance Rate 4,500 MTU/yr and Starting Date in 2060.

3.3 Comparison with Repackaging

Comparison with the reference repackaging cases is done with regard to the additional storage capacity required at the ISF and additional emplacement time (extended storage) for each DPC direct disposal alternative listed in Table 1.

As it was discussed in Section 2, the maximum ISF capacity in the reference repackaging case is a function of the repository starting date and the ISF/repository acceptance rates (Figure 1). These capacities are provided in Table 2. In the reference repackaging cases, the period of time from the repository starting date to end of ISF operations is either 31 years (4,500 MTU/year) or 47 years (3,000 MTU/year) regardless of the repository starting date as explained in Section 2. The additional emplacement time for the 18 alternatives being studied here is calculated compared to these two durations. Note that the maximum ISF capacity may be larger and the ISF operational time may be longer than the ones above calculated using a simplified approach. This approach is conservative because it has a potential to overestimate the difference between the direct DPC disposal alternatives and the corresponding repackaging cases.

The last year of the repository operations in the DPC direct disposal alternatives is considered to be the year in which 98% of the total inventory is emplaced. It was assumed that the remaining 2% (2,775 MTU) will be disposed of at a later time at which the full-scale operations at the repository will be mostly completed. An example of the inventory that falls within this 2% is discussed in Section 3.4.

The results of the logistic simulations are summarized in Table 2. Only three DPC alternatives require additional ISF capacity compared to the corresponding repackaging cases. These are: 6 kW thermal power limit with the repository starting date in 2036 and 2048 alternatives and 10 kW thermal power limit with the repository starting date in 2036 alternative. The additional storage capacity in the range of 11,300 to 70,000 MTU is required for both, 3,000 MTU/year and 4,500 MTU/year ISF/repository acceptance rates. By introducing small STADs the need in the additional storage capacity is eliminated for all the considered thermal power limits and the repository starting dates for both, 3,000 MTU/year and 4,500 MTU/year ISF/repository acceptance rates. Consequently, no additional capital costs are associated with these alternatives.

The additional emplacement time is required for all 6 kW thermal power limit alternatives. This additional time ranges from 55 to 95 years for the DPCs-only alternatives. Introducing small STADs reduces this range to between 36 to 69 years. The additional emplacement time is also required for 10 kW thermal power limit DPCs-only alternatives. The additional time ranges from 5 to 45 years. Introducing STADs reduces this range to between 0 and 19 years. The additional emplacement time will result in additional operational costs.

Introducing small STADs almost eliminates the additional emplacement time in the 10 kW thermal power limit alternatives when the ISF/repository acceptance rate is 3,000 MTU/year. The 18 kW thermal power limit alternatives do not require additional emplacement time, regardless of the repository acceptance rate.

Table 2. Summary of the ISF Storage Capacities and Operational Times for the 18 Alternatives.

Repository Starting Date	Thermal Limit in kW	Fuel Loading Scenario	Max ISF Storage in MTU at Fixed Max Repository Acceptance Rate		Last Year of Operations 3,000/4,500 MTU/yr	Additional ISF Capacity in MTU at Fixed Max Repository Acceptance Rate		Additional Emplacement Time in Years at Fixed Max Repository Acceptance Rate		Age at Emplacement in Years for 3,000 MTU/yr Max Repository Acceptance Rate	
			3,000 MTU/yr	4,500 MTU/yr		3,000 MTU/yr	4,500 MTU/yr	3,000 MTU/yr	4,500 MTU/yr	Average	Maximum
	6	DPC only	102,701	114,804	2162	69,701	65,304	79	95	79	146
	6	DPCs and STADs	33,000	49,500	2119	0	0	36	52	46	128
	10	DPC only	53,245	80,444	2112	20,245	30,944	29	45	55	90
2036	10	DPCs and STADs	33,000	49,500	2083/2067	0	0	0	6	46	82
	18	DPC only	33,000	49,500	2083/2067	0	0	0	7	51	82
	18	DPCs and STADs	33,000	49,500	2083/2067	0	0	0	0	49	81
	NA	Repackaging	33,000	49,500							
	6	DPC only	102,701	114,807	2162	33,701	11,307	67	83	84	146
	6	DPCs and STADs	69,000	102,735	2145	0	0	50	66	62	140
	10	DPC only	69,000	103,500	2112	0	0	17	33	63	90
2048	10	DPCs and STADs	69,000	103,500	2095	0	0	0	16	58	90
	18	DPC only	69,000	103,500	2095/2079	0	0	0	0	61	85
	18	DPCs and STADs	69,000	103,500	2095/2079	0	0	0	0	59	85
	NA	Repackaging	69,000	103,500							
	6	DPC only	105,000	134,235	2162	0	0	55	71	88	146
	6	DPCs and STADs	105,000	134,235	2160	0	0	53	69	86	146
	10	DPC only	105,000	134,235	2112	0	0	5	21	73	97
2060	10	DPCs and STADs	105,000	134,235	2110	0	0	3	19	73	97
	18	DPC only	105,000	134,233	2107/2091	0	0	0	0	72	97
	18	DPCs and STADs	105,000	134,235	2107/2091	0	0	0	0	72	97
	NA	Repackaging	105,000	138,735							

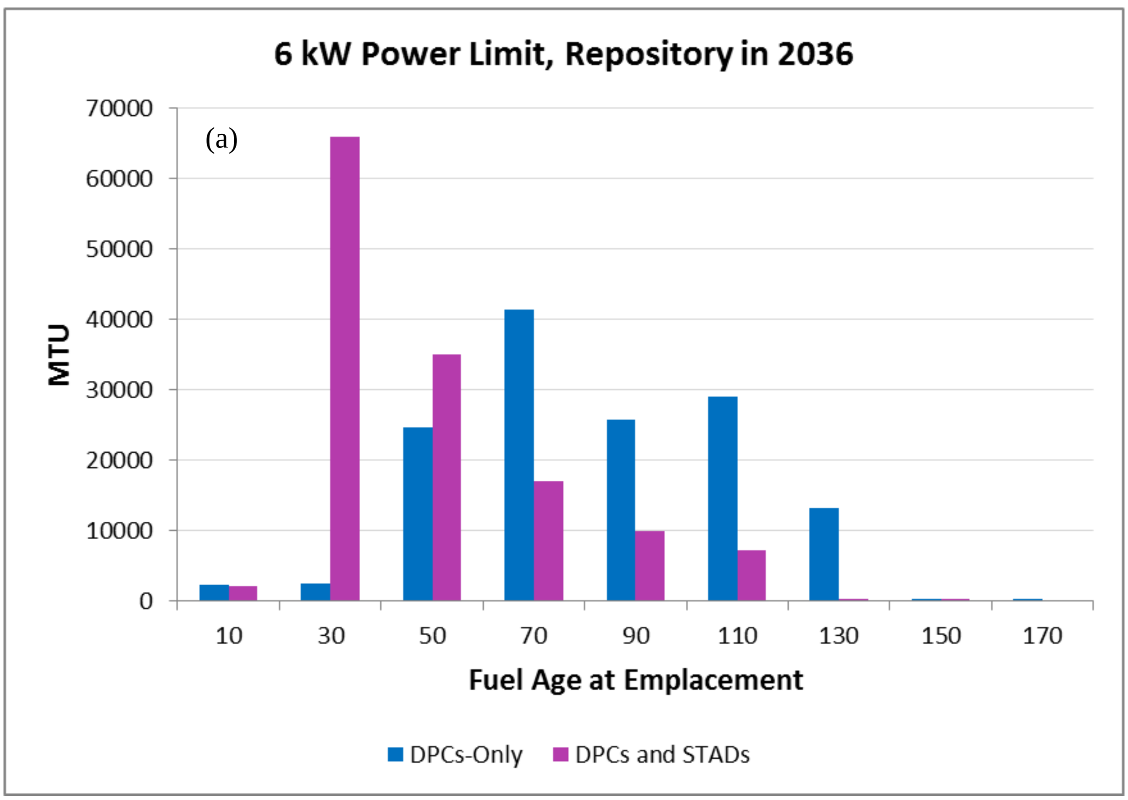
NOTE: The age at emplacement is for the 98% of the inventory that was emplaced by the last year of repository operations. Only one value is shown for the last year of operations if it is the same for 3,000 and 4,500 MTU/yr maximum repository acceptance rate.

3.4 Fuel Age at Emplacement

The dry storage installations (ISFSIs) in the US are presently licensed for 20 years, with the possibility of extension to a total of 60 years as defined in NUREG-1927, March 2011, p. 1 [Ref. 2]. Consequently, storing UNF for more than 60 years may pose regulatory problems. In addition some other problems might arise as DPCs age. As a result, the age of fuel at the emplacement is an important factor that may affect the feasibility of the direct disposal of DPCs. This analysis evaluated fuel age at disposal to identify age profiles for the overall inventory, that could be achievable under thermal, logistic, and other constraints.

The distributions of fuel age at emplacement are shown in Figure 11-13 (6 kW; 10 kW; and 18 kW thermal power limits) for the repository starting date 2036, in Figures 14-16 (6 kW; 10 kW; and 18 kW thermal power limits) for the repository starting date 2048, and in Figure 17-19 (6 kW; 10 kW; and 18 kW thermal power limits) for the repository starting date 2060. The average and maximum age at emplacement for the different DPC alternatives are provided in Table 2.

The purpose of Figures 11-19 is to evaluate the impacts from introducing small STADs on the fuel age at emplacement. Introducing small STADs allows accelerated disposal of the UNF in the 6 kW thermal power limit alternatives with the repository starting dates in 2036 and 2048. It also allows to somewhat accelerate the disposal of the UNF of the 10 kW thermal power limit alternatives with the repository starting date in 2036. There are very small differences between the DPCs only and DPCs and STADs alternatives for all the other alternatives.



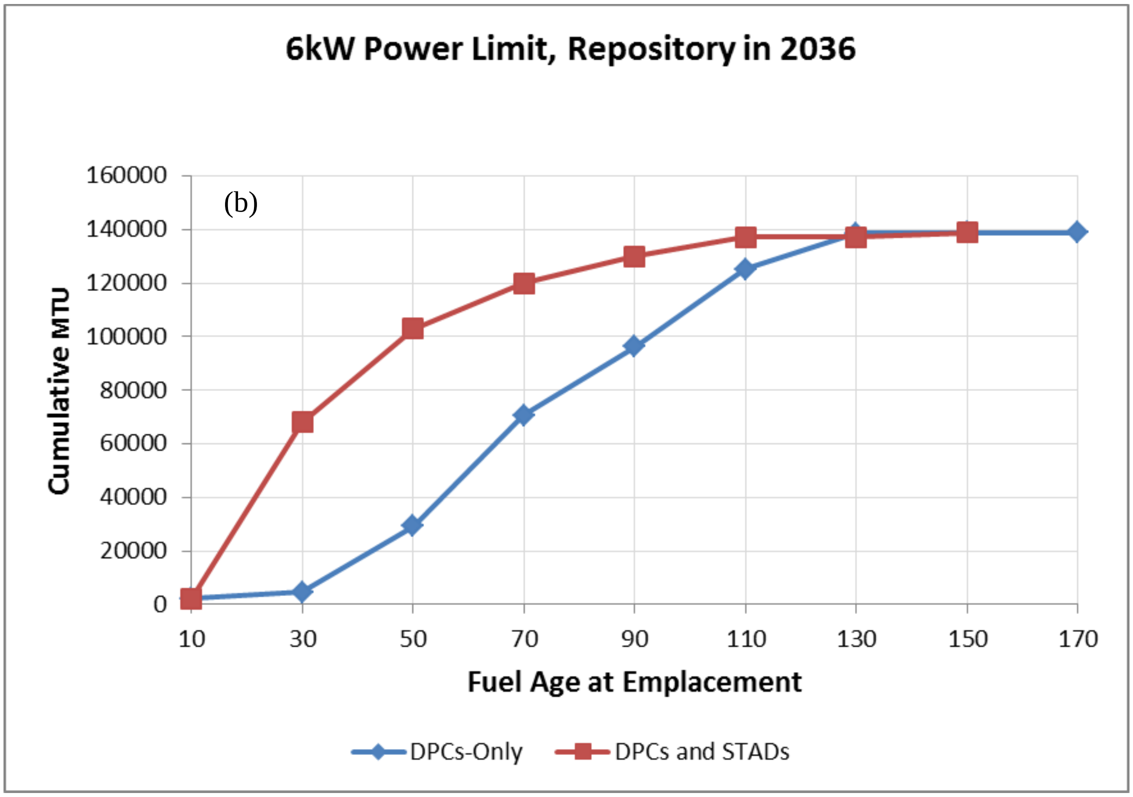
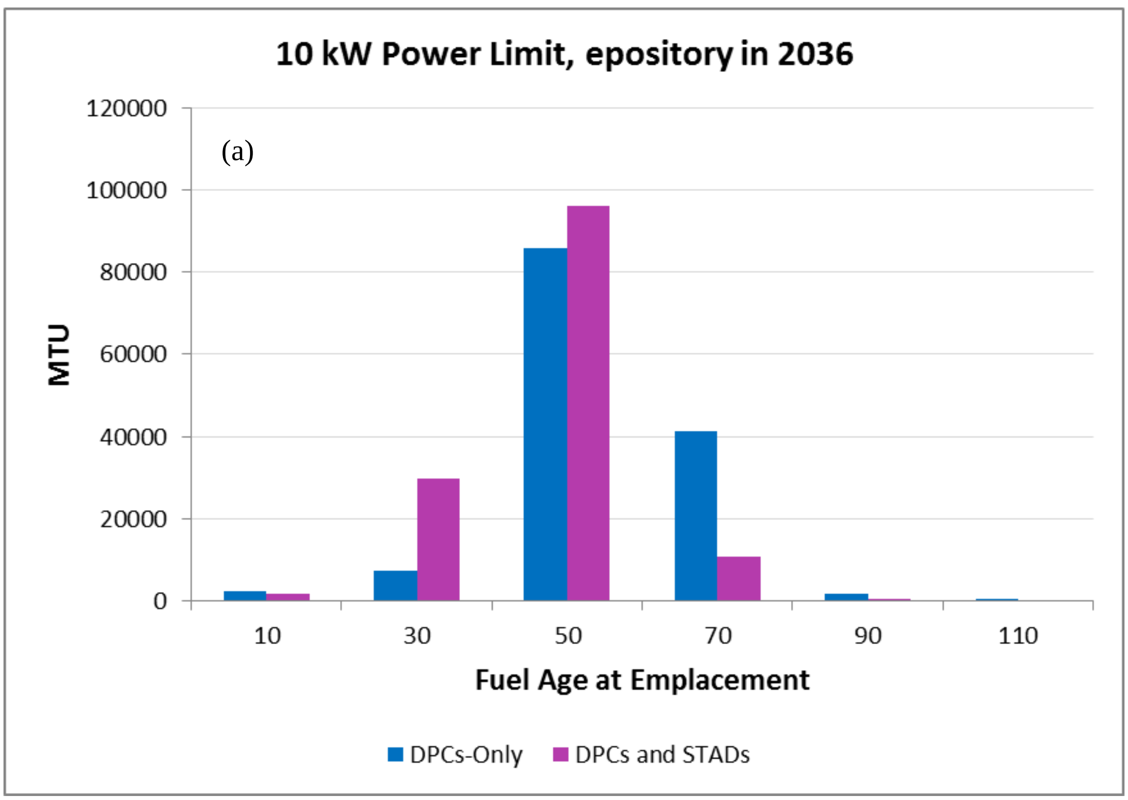


Figure 11. Inventory Age (a) and Cumulative Inventory Age (b) at Emplacement for a Repository with a 6 kW Thermal Limit and 2036 Starting Date.



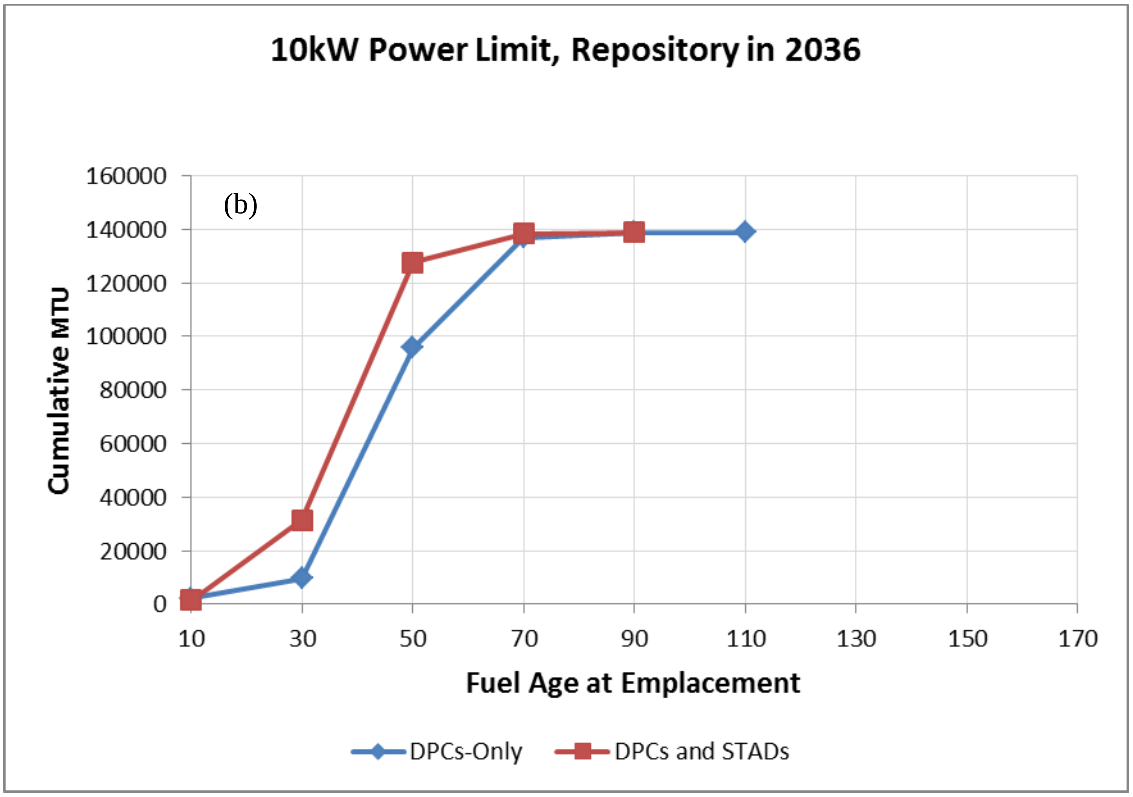
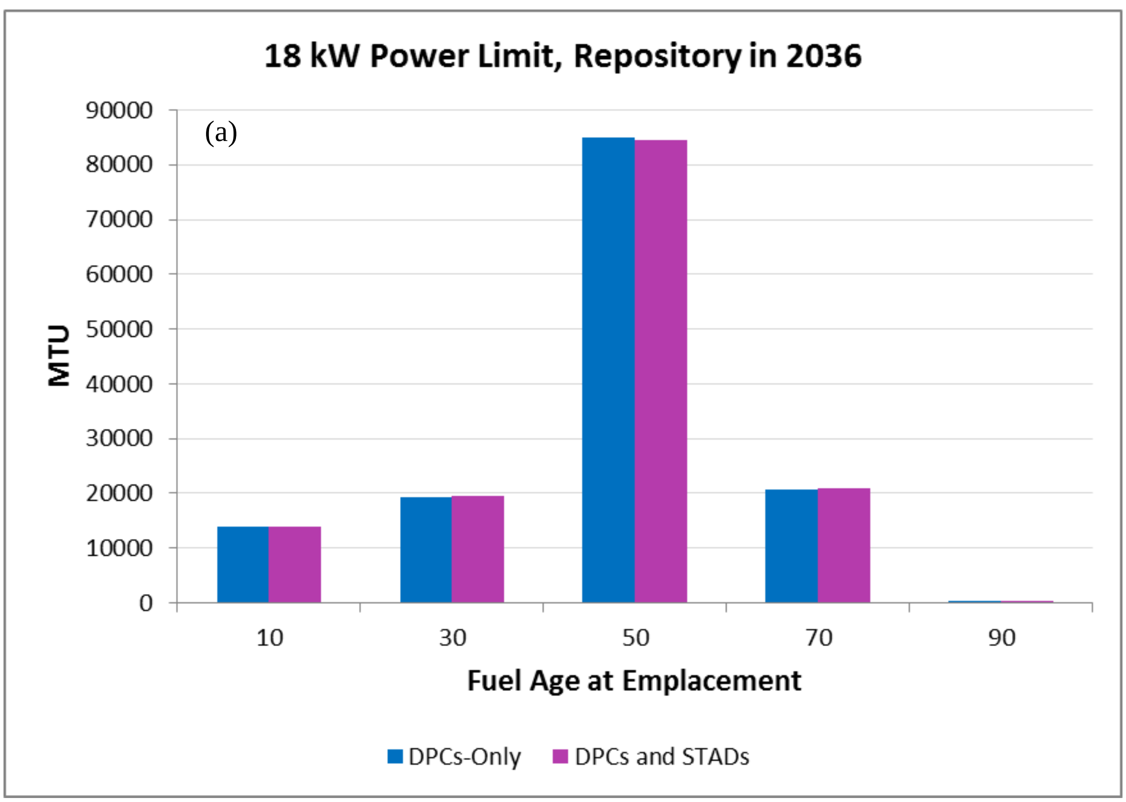


Figure 12. Inventory Age (a) and Cumulative Inventory Age (b) at Emplacement for a Repository with a 10 kW Thermal Limit and 2036 Starting Date.



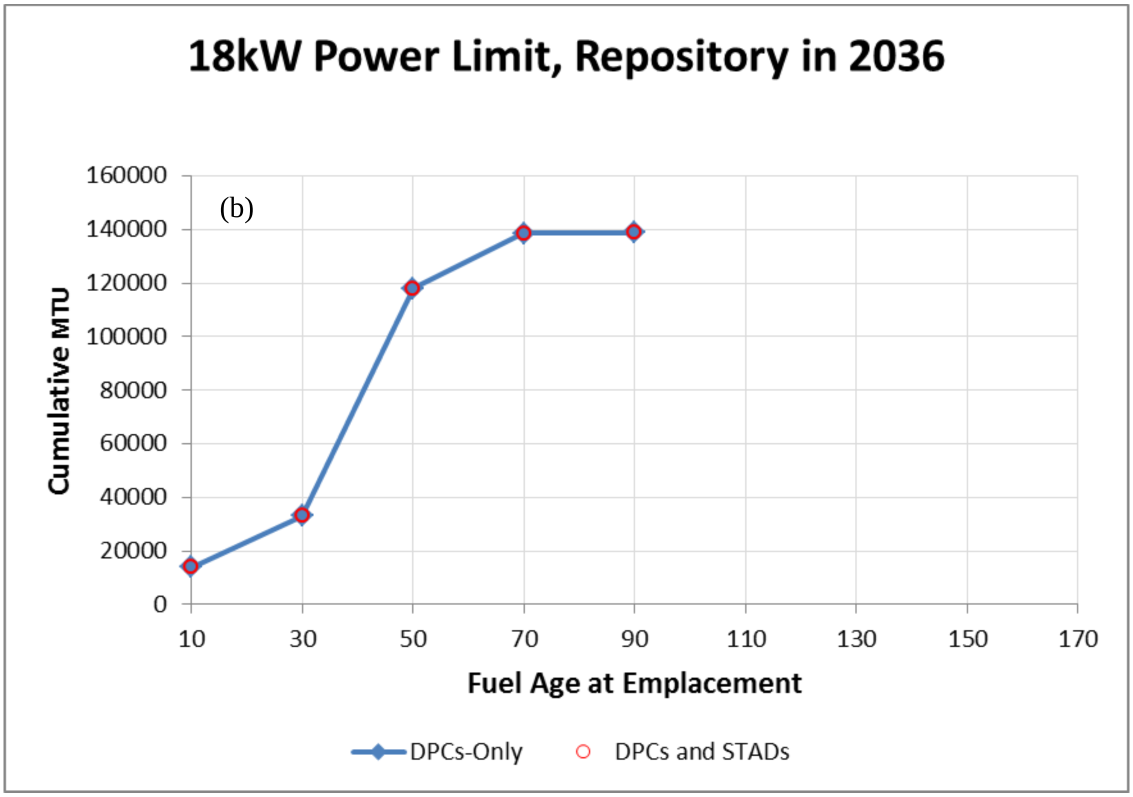
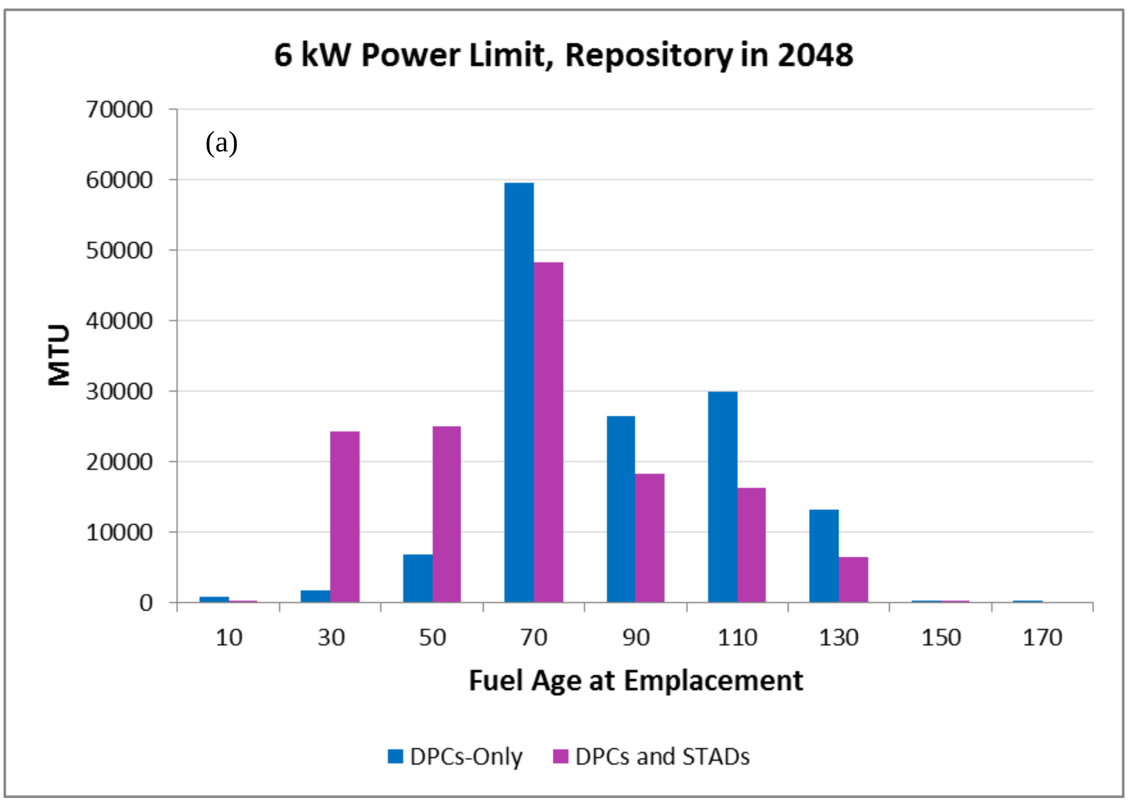


Figure 13. Inventory Age (a) and Cumulative Inventory Age (b) at Emplacement for a Repository with an 18 kW Thermal Limit and 2036 Starting Date.



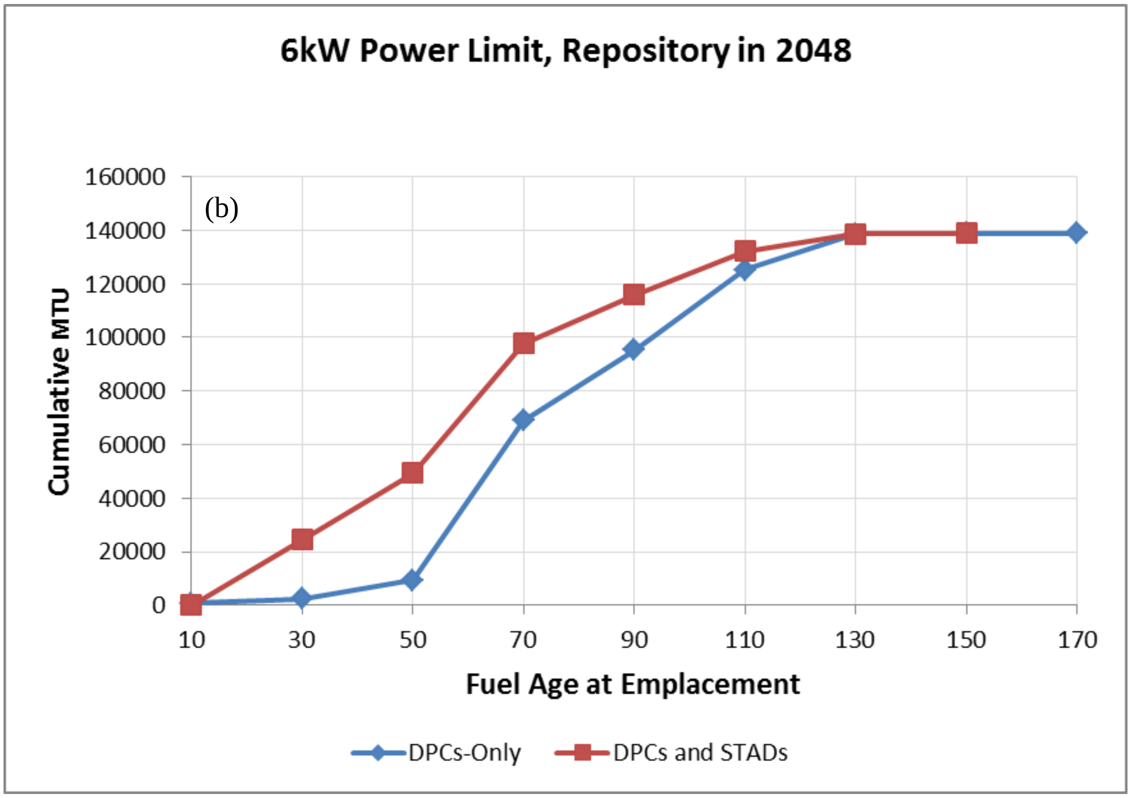
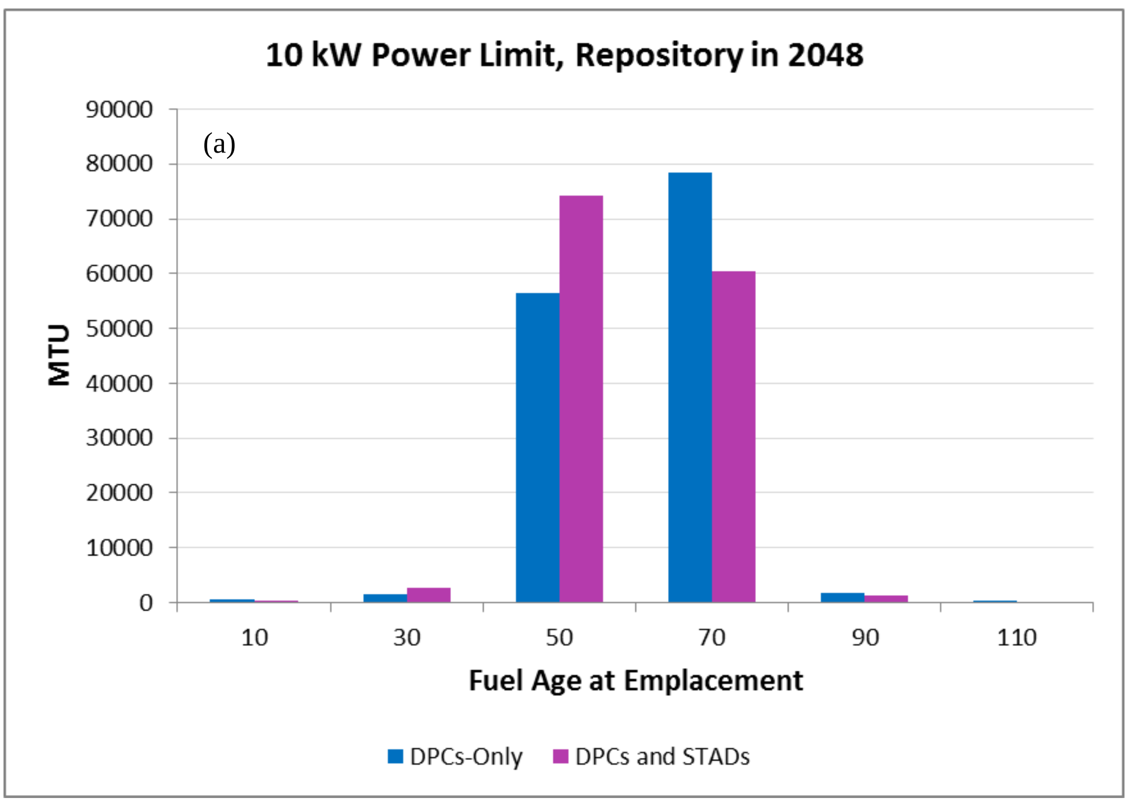


Figure 14. Inventory Age (a) and Cumulative Inventory Age (b) at Emplacement for a Repository with a 6 kW Thermal Limit and 2048 Starting Date.



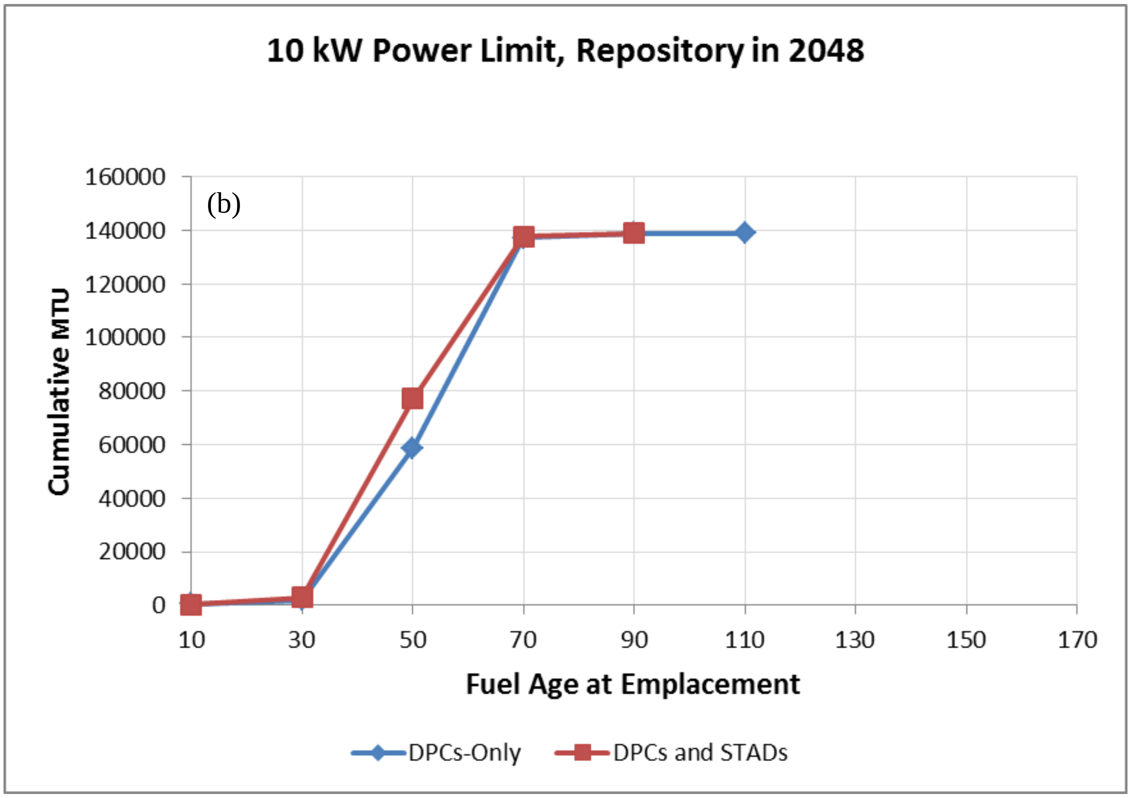
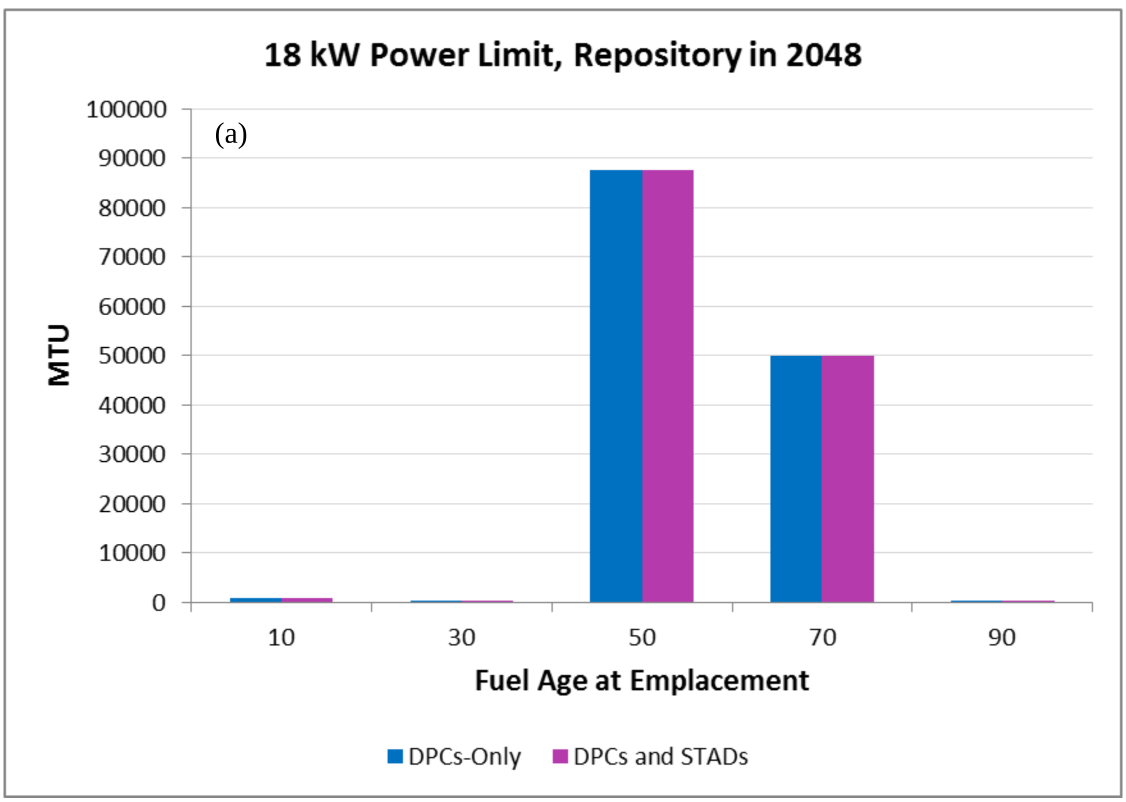


Figure 15. Inventory Age (a) and Cumulative Inventory Age (b) at Emplacement for a Repository with a 10 kW Thermal Limit and 2048 Starting Date.



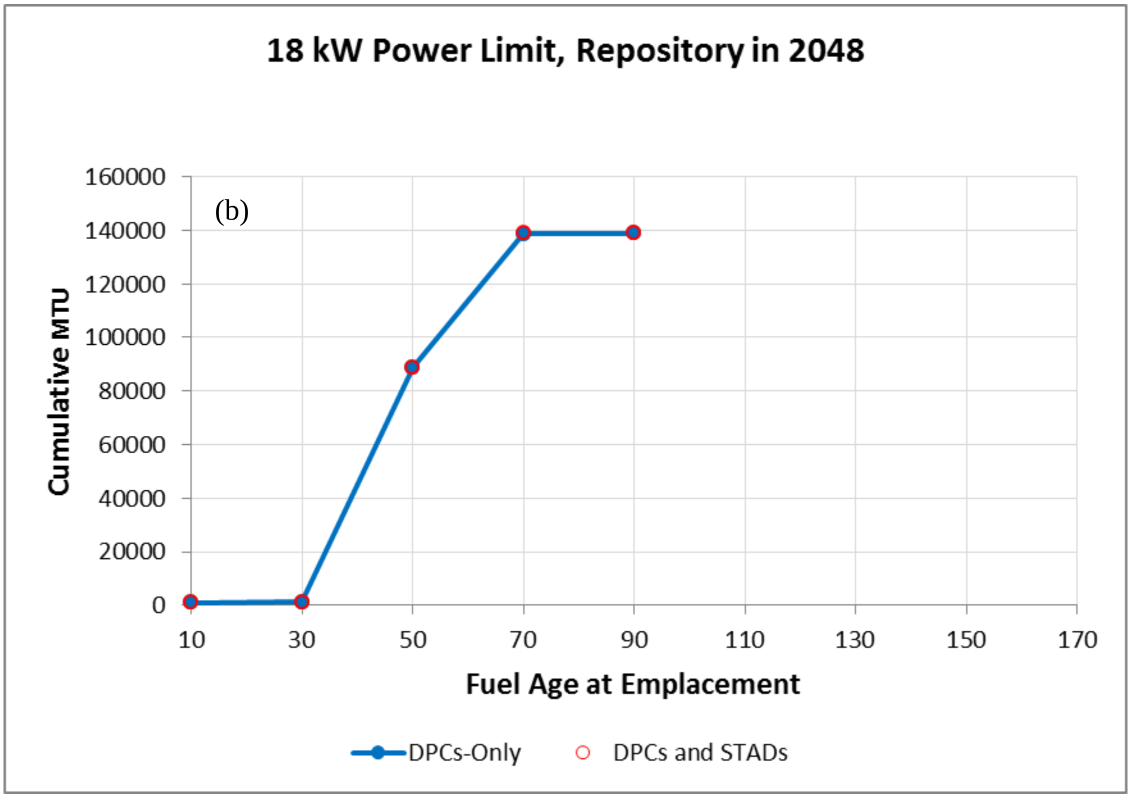
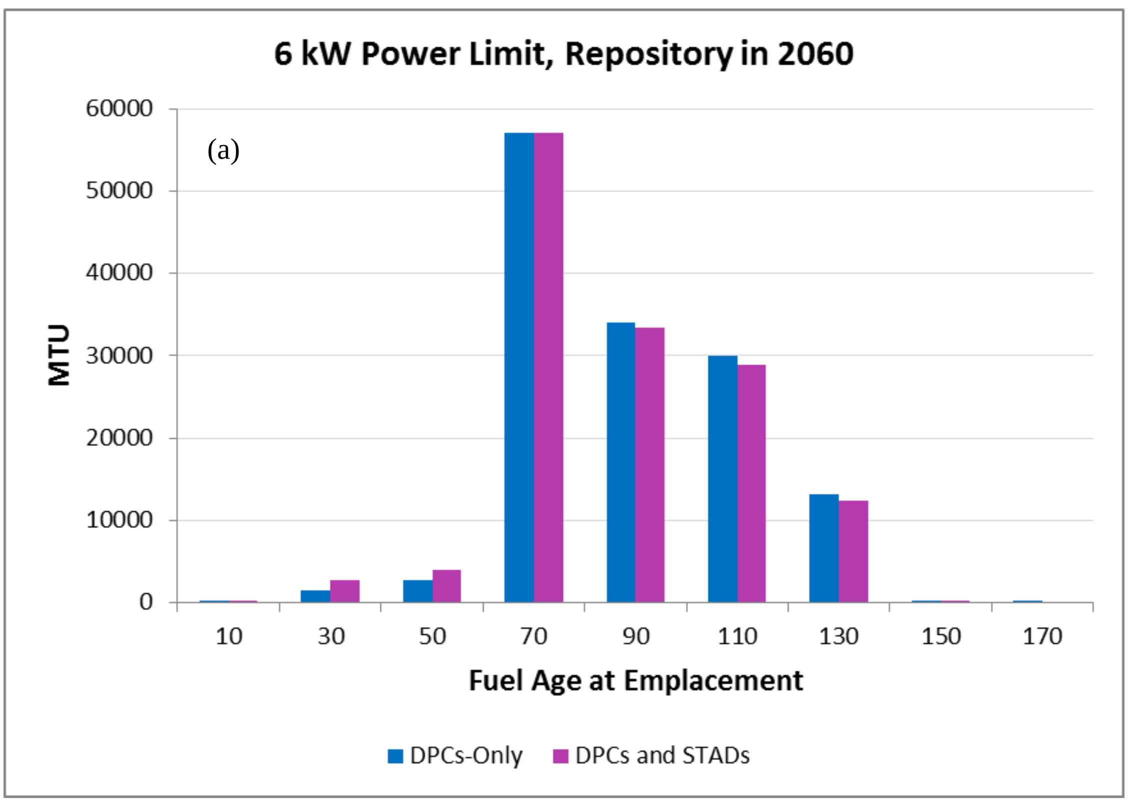


Figure 16. Inventory Age (a) and Cumulative Inventory Age (b) at Emplacement for a Repository with an 18 kW Thermal Limit and 2048 Starting Date.



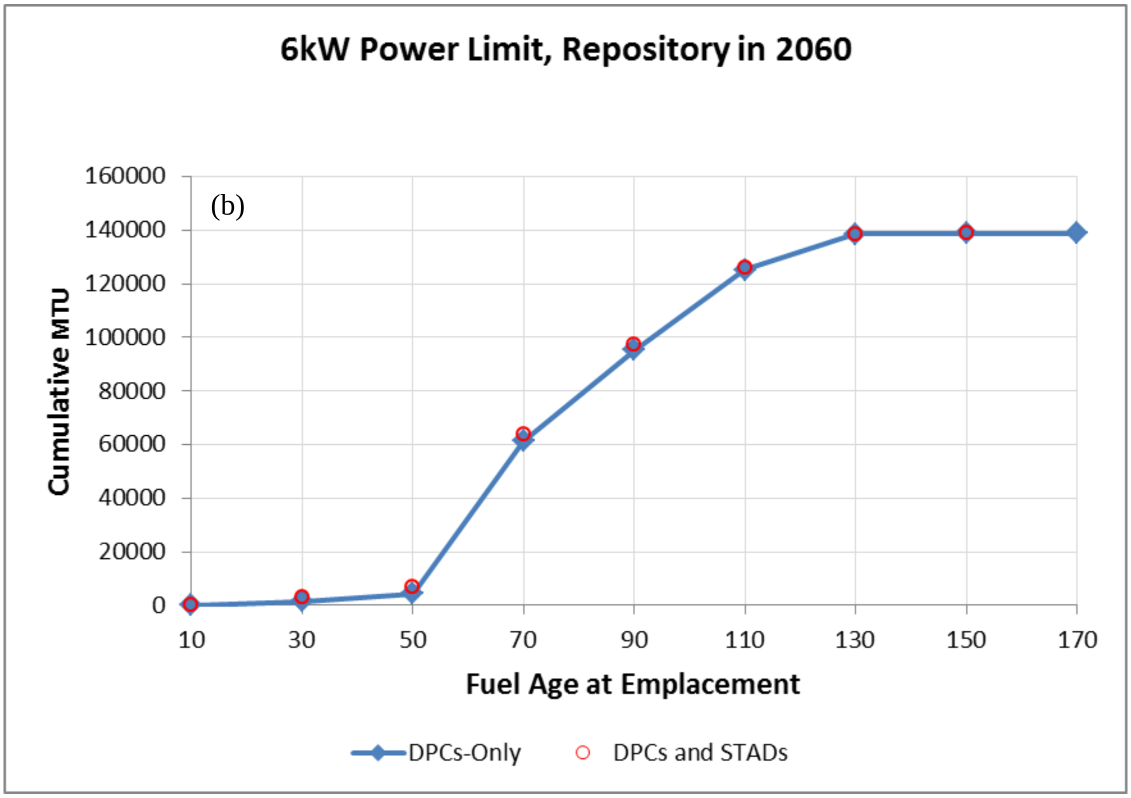
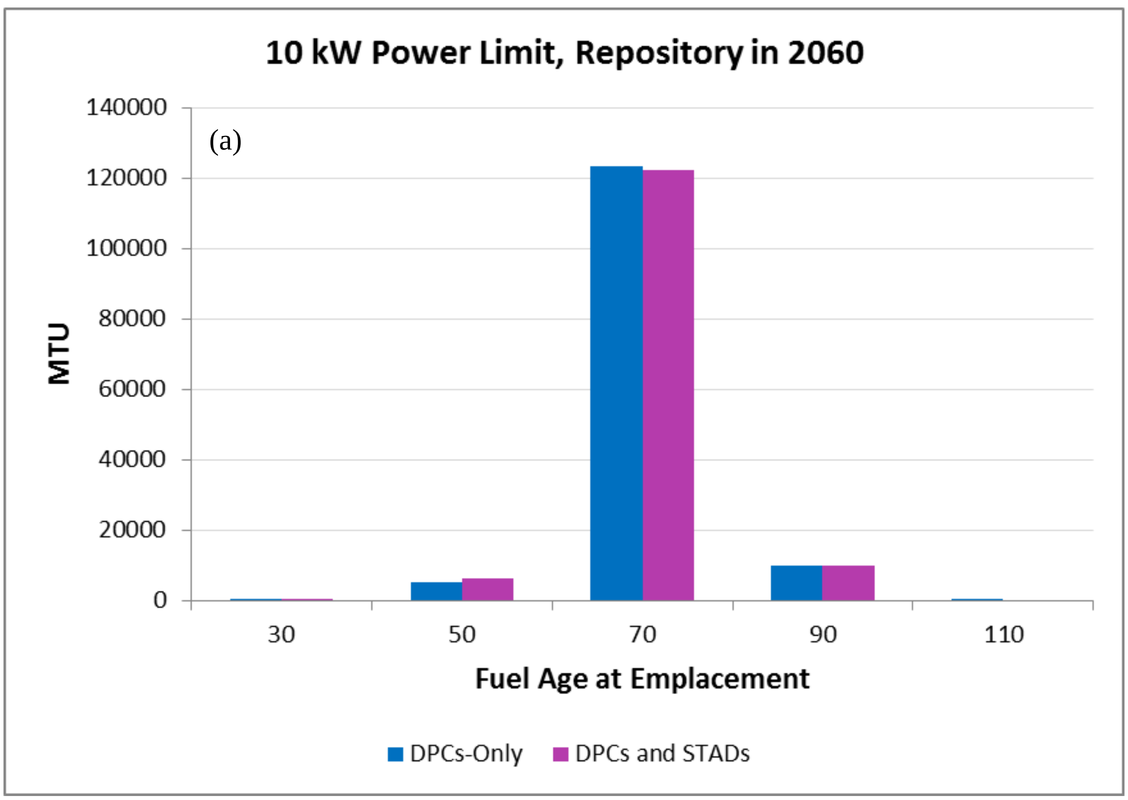


Figure 17. Inventory Age (a) and Cumulative Inventory Age (b) at Emplacement for a Repository with a 6 kW Thermal Limit and 2060 Starting Date.



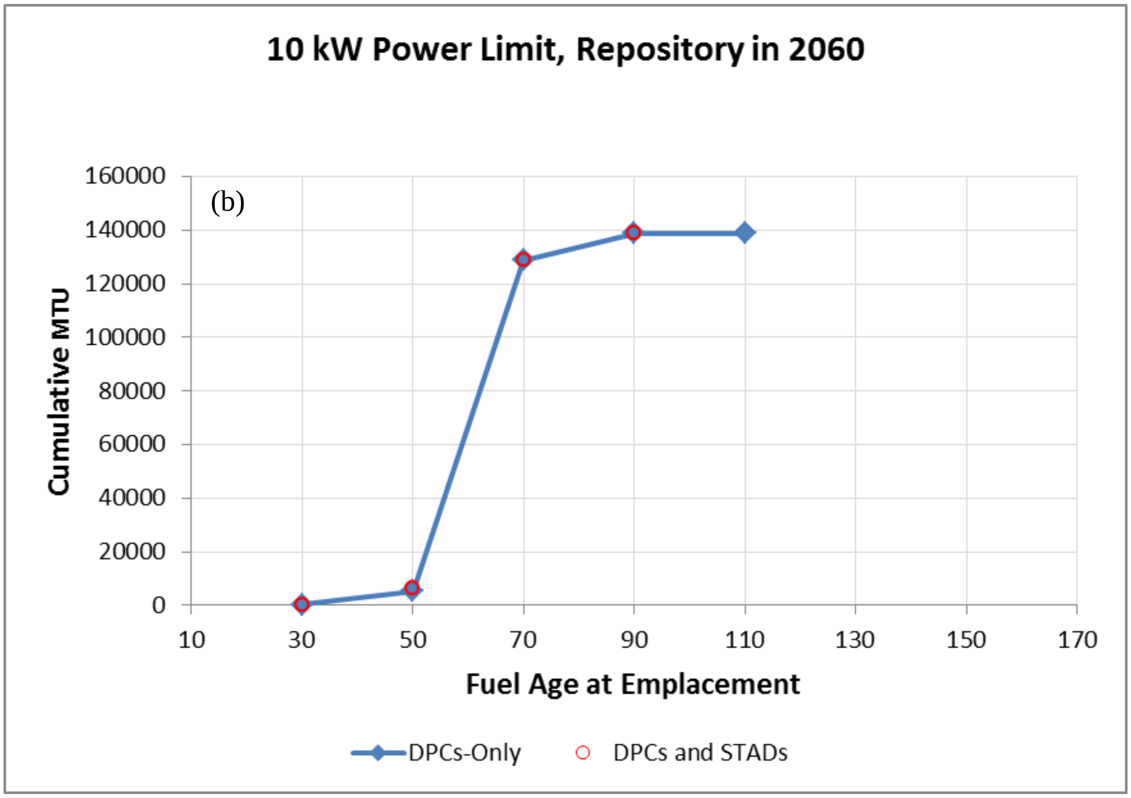
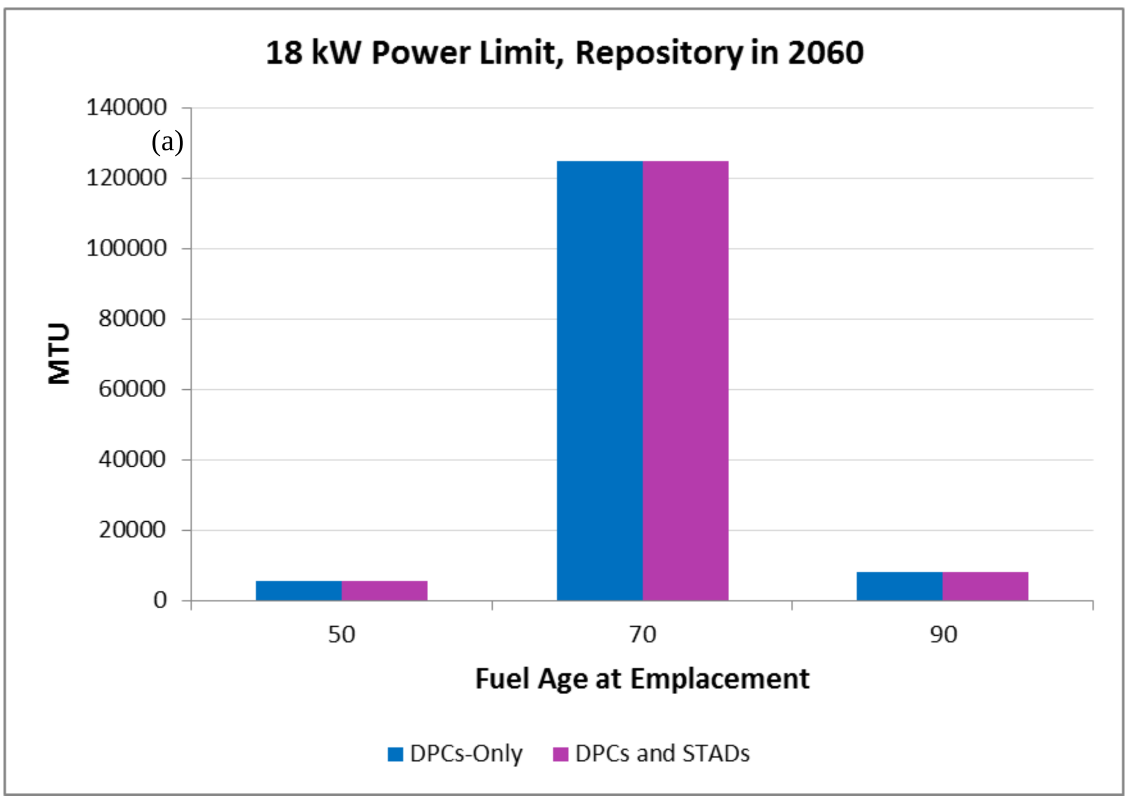


Figure 18. Inventory Age (a) and Cumulative Inventory Age (b) at Emplacement for a Repository with a 10 kW Thermal Limit and 2060 Starting Date.



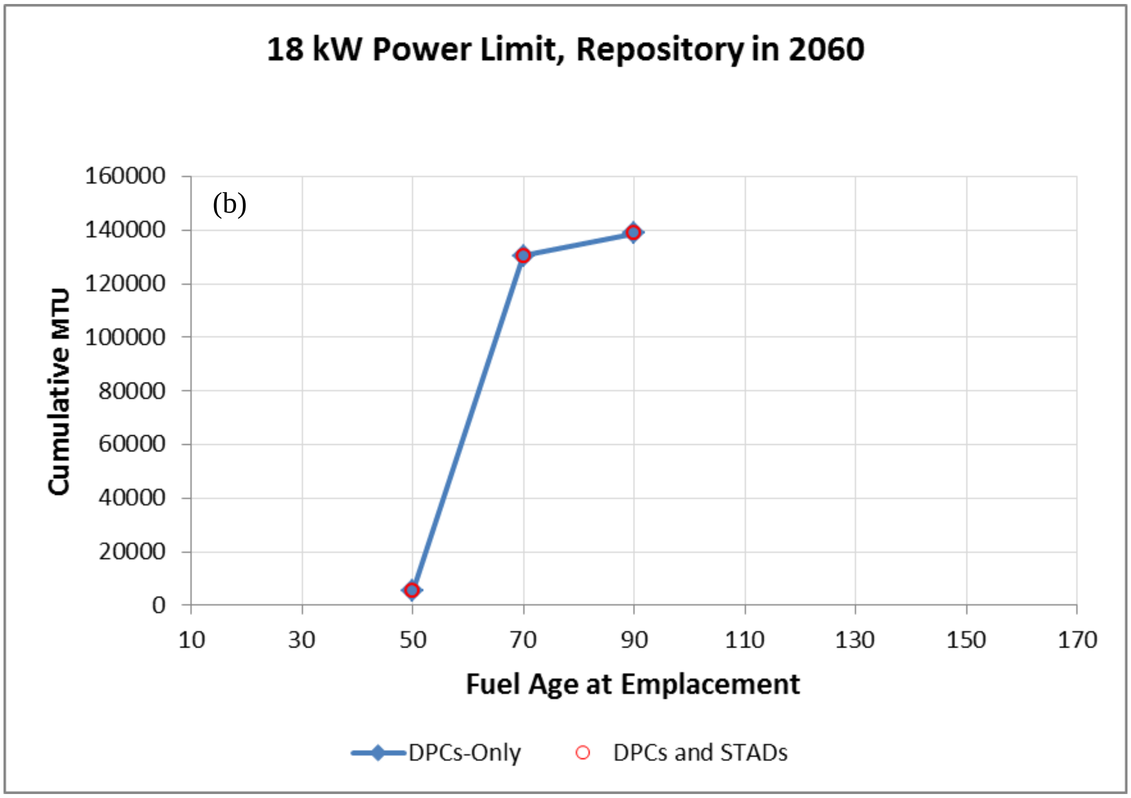
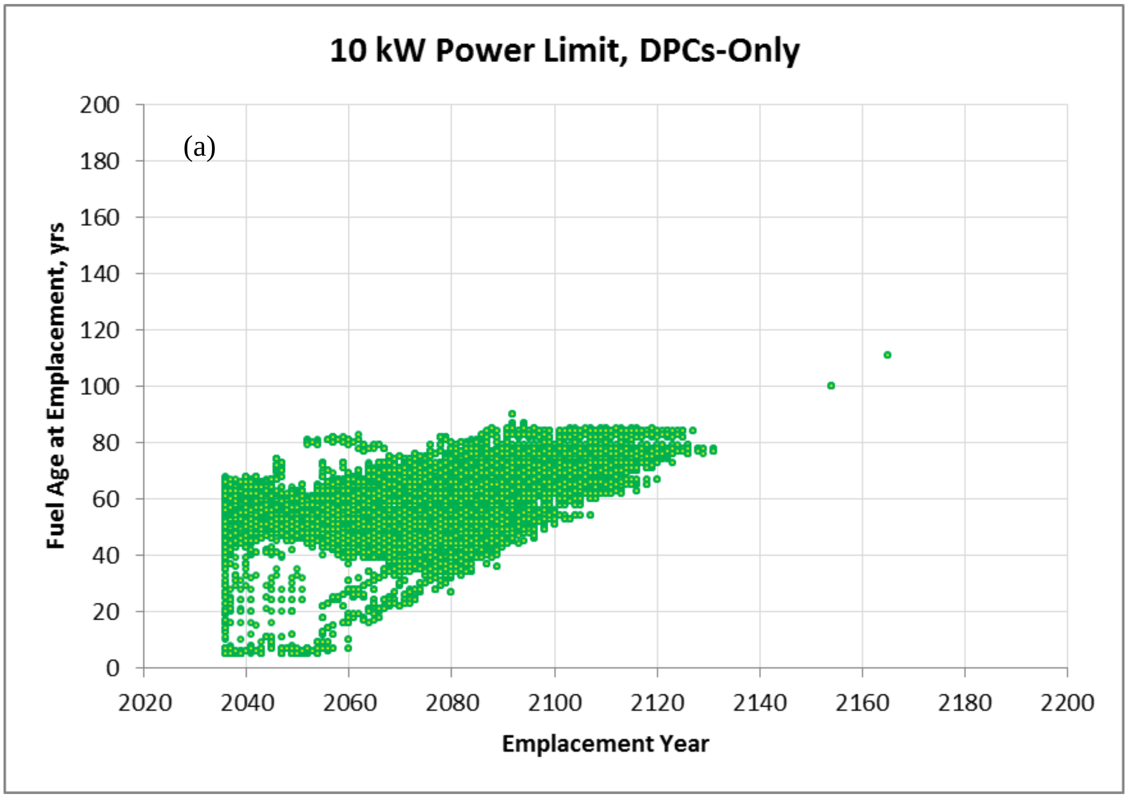


Figure 19. Inventory Age (a) and Cumulative Inventory Age (b) at Emplacement for a Repository with an 18 kW Thermal Limit and 2060 Starting Date.

The age of each fuel batch at emplacement for an alternative with the repository starting date of 2036 and thermal power limit of 10 kW is shown in Figure 20 (a and b). The fuel batch is the smallest logistic unit that is assigned the same burnup and enrichment and that consists of assemblies discharged on the same date and at the same reactor site. Figure 20 demonstrates that the age of fuel varies from 5 to 80 years during the first 25 years of emplacement. The age range becomes smaller in the last 10 years, –ranging from 60 to 85 year old. The alternative with the DPCs and STADs has a trend similar to the DPCs-only case, but is significantly smaller spread in time. Also, the impact from introducing STADs becomes noticeable around 2060. From this time on, the age of the fuel at emplacement continues to increase for DPCs and decrease for STADs. The alternatives with the repository starting dates of 2048 and 2060 have smaller differences between the DPCs-only and DPCs with STADs cases than the differences evident from Figures 20a and 20b.

The outliers in Figure 20a with the age at emplacement of 100 years and 111 years are an example of 2% of the inventory not included in calculating the additional storage time required at ISF as explained in Section 3.3. This inventory is in two DPCs. The first DPC has 32 PWR assemblies with average burnup 60 GWD/MTU which are 100 years old at the time of emplacement. The second DPC has 9 PWR assemblies (it is not fully loaded) with average burnup 81 GWD/MTU which are 111 years old at the time of emplacement.



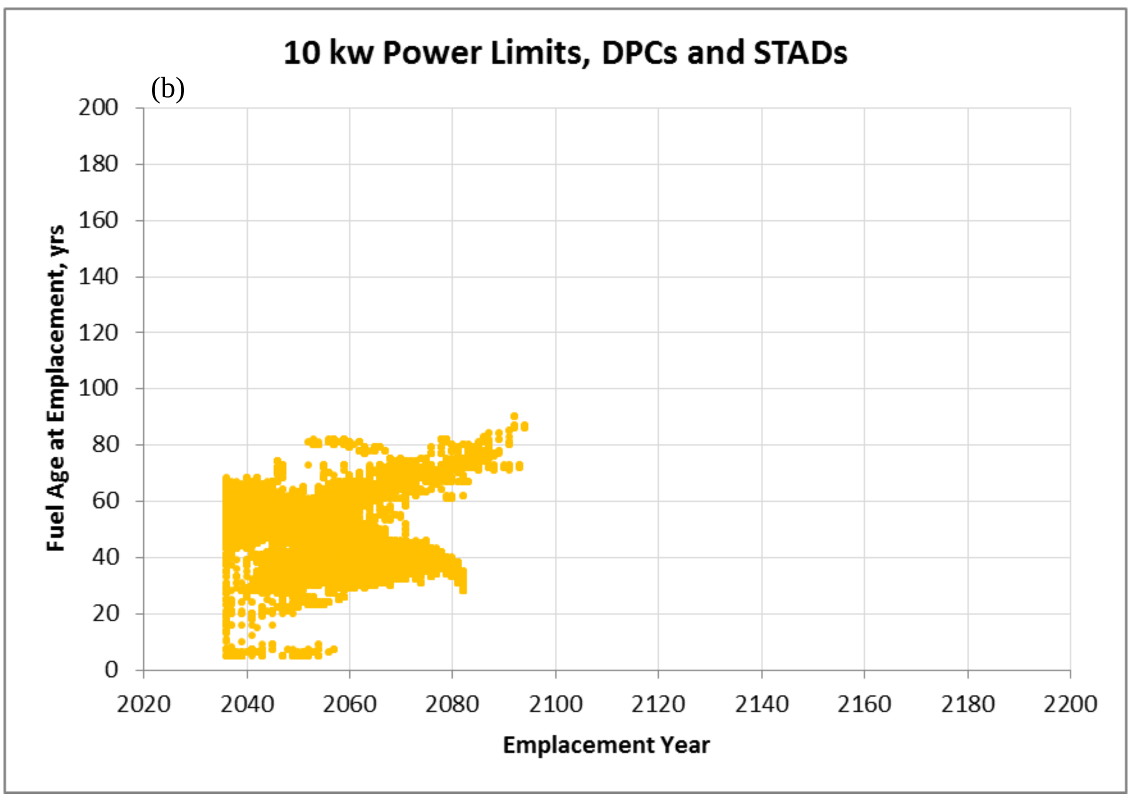


Figure 20. Fuel Age at Emplacement for a Repository with a 10 kW Thermal Limit and 2036 Starting Date: (a) DPCs only and (b) DPCs and STADS.

Average age at emplacement as a function of the repository starting date and thermal power limit, as shown in Figure 21a for the DPCs-only alternatives and in Figure 21b for the DPCs and small STADs alternatives.

The average age at emplacement experiences linear increase as a function of the repository starting date in both fuel loading scenarios, DPCs only and DPCs and small STADs. These dependencies are practically the same for the DPCs only 10 kW an 18 kW thermal power limit alternatives and for the DPCs with small STADs 10 kW an 18 kW thermal power limit alternatives.

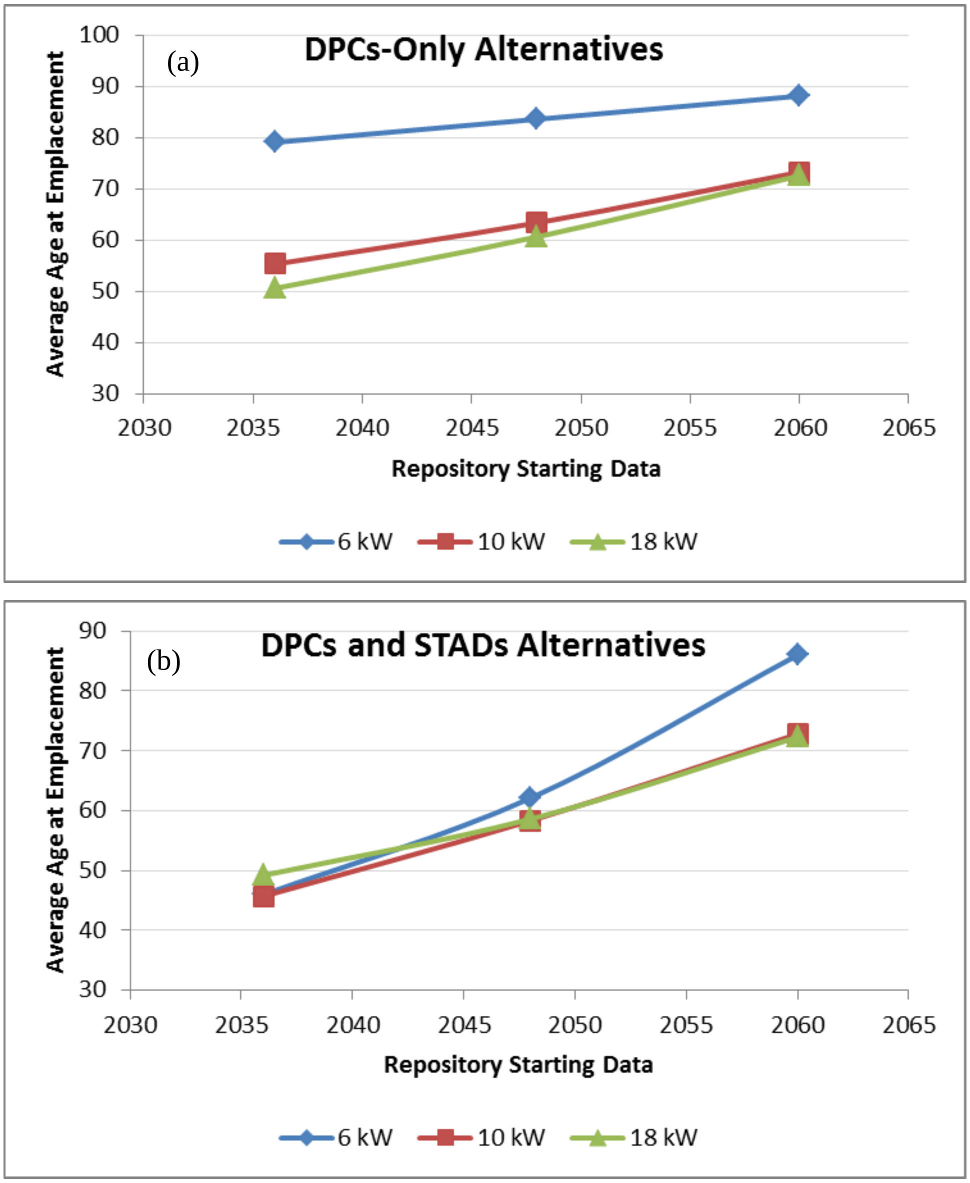
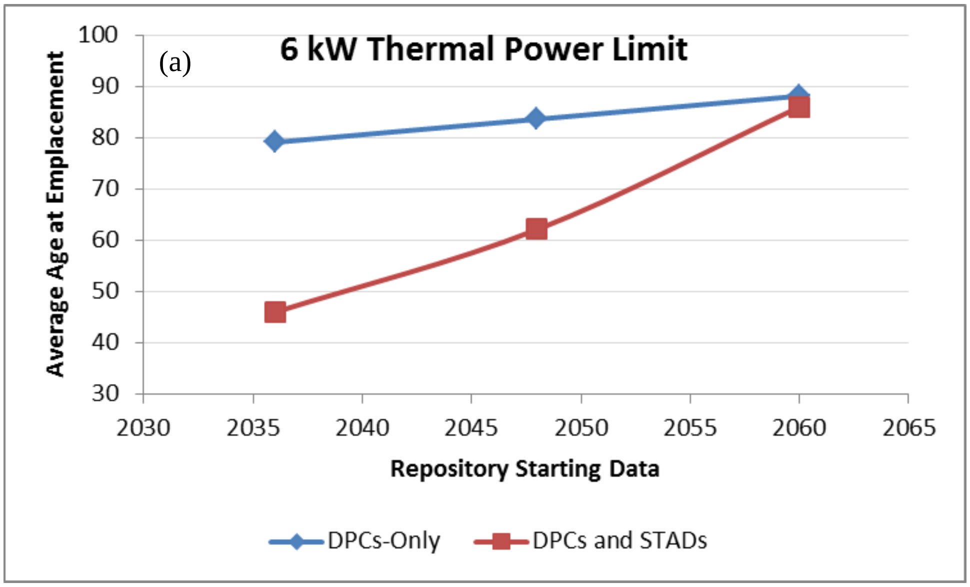
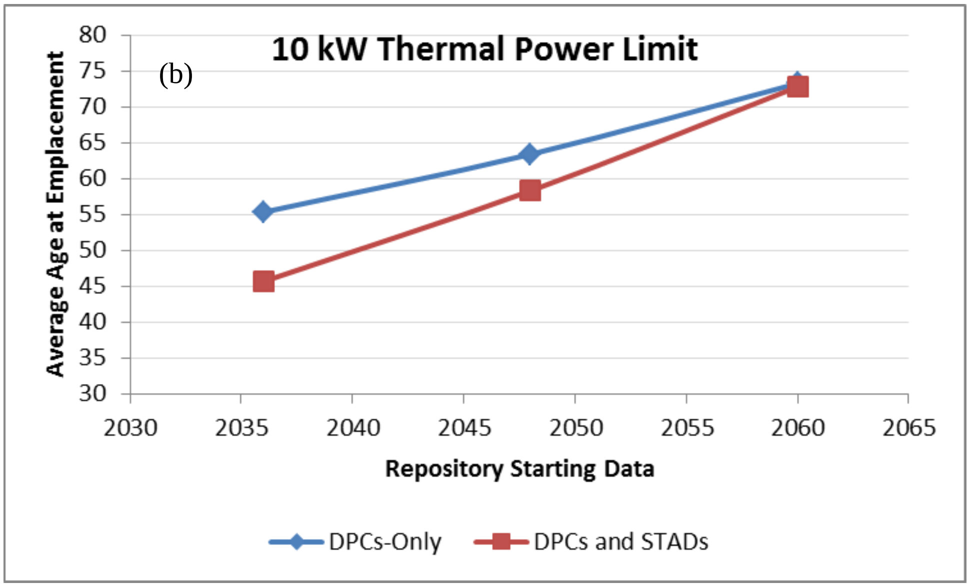


Figure 21. Average Age at Emplacement as a Function of Repository Starting Date and Emplacement Thermal Limit: (a) DPCs only and (b) DPCs and small STADS.

Average age at emplacement as a function of the repository starting date and fuel loading scenario is shown in Figure 22 for the different thermal power limits. Implementing small STADs allows for reducing the average age at emplacement for the 6 kW and to some extent 10 kW thermal power limit alternatives with the repository starting dates in 2036 and 2048. The average age at emplacement of the 18 kW thermal power limit alternatives is not affected by introducing small STADs. The average age at emplacement of all the alternatives with the repository starting date in 2060 is also not affected by introducing small STADs.





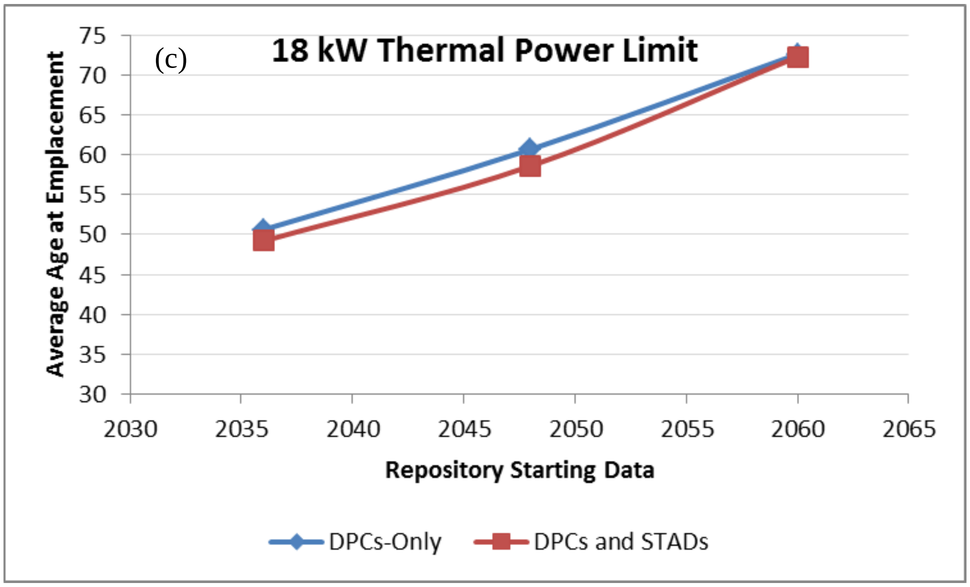


Figure 22. Average Age at Emplacement as a Function of Emplacement Thermal Limit and Fuel Loading Scenario: (a) 6 kW; (b) 10 kW; and (c) 18 kW.

As it was shown above, the biggest impact from introducing small STADs is observed for the alternative with the 6 kW thermal power limit and early repository starting date (2036). This alternative was examined to evaluate the differences between the inventory in DPCs and inventory in STADs. The differences in the inventory properties are shown with regard to the age at emplacement (Figure 23a and Figure 23b) and burnup (Figure 24a and Figure 24b). Figures 23b and 24b demonstrate that 40% of the inventory is disposed of in DPCs and 60% of the inventory is disposed of in STADs. Figures 23a and b demonstrate that the majority of fuel in STADs is 30 years old or younger. The fuel in DPCs is 50 years old or older. Figures 24a and b demonstrates that the burnup of the fuel in STADs is mostly 45 GWD/MTU or higher. The burnup of the fuel in DPCs is mostly 35 to 45 GWD/MTU or lower.

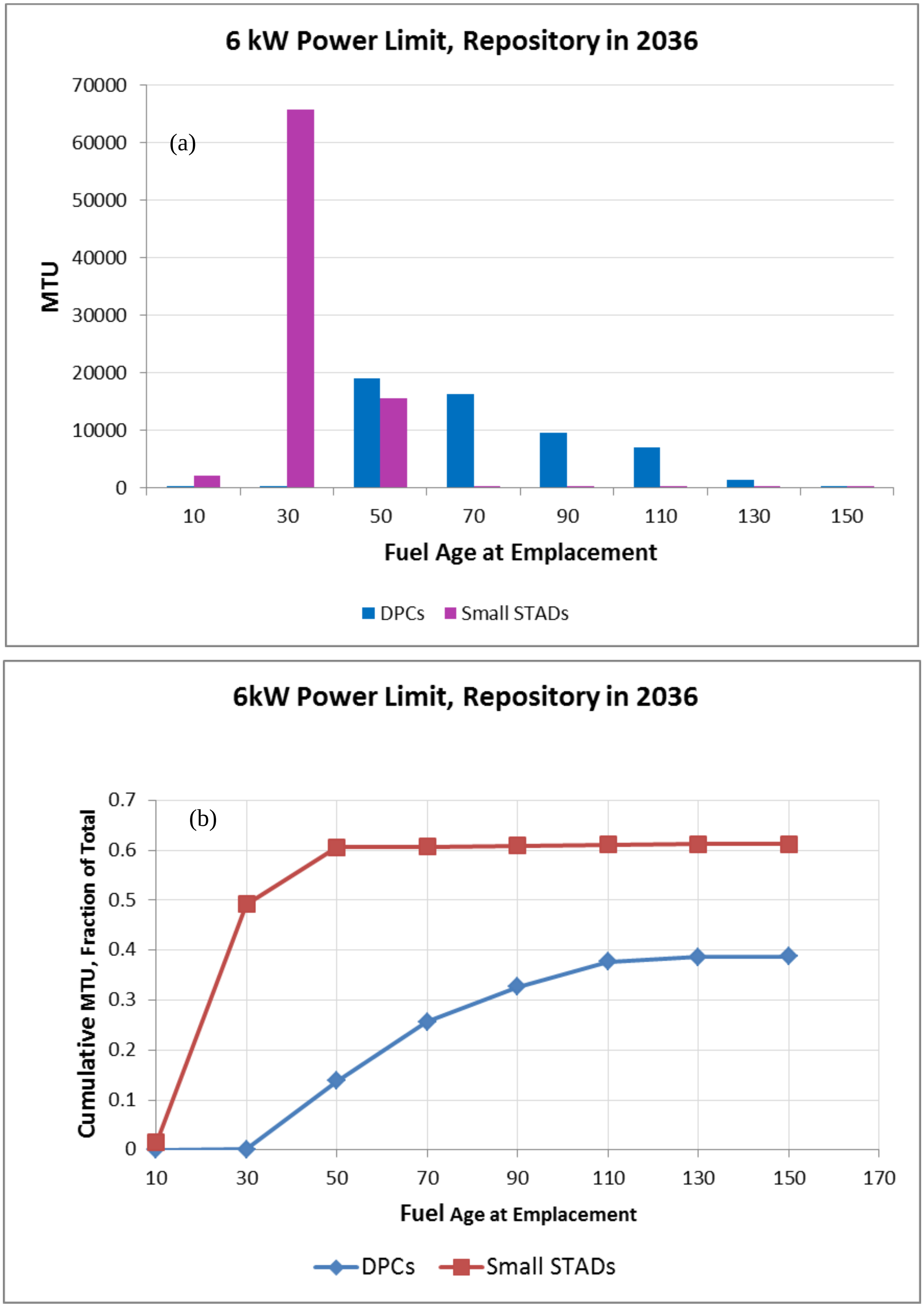


Figure 23. Age of Fuel in DPCs and STADs at Emplacement, 6 kW Thermal Power Limit, Repository in 2036.

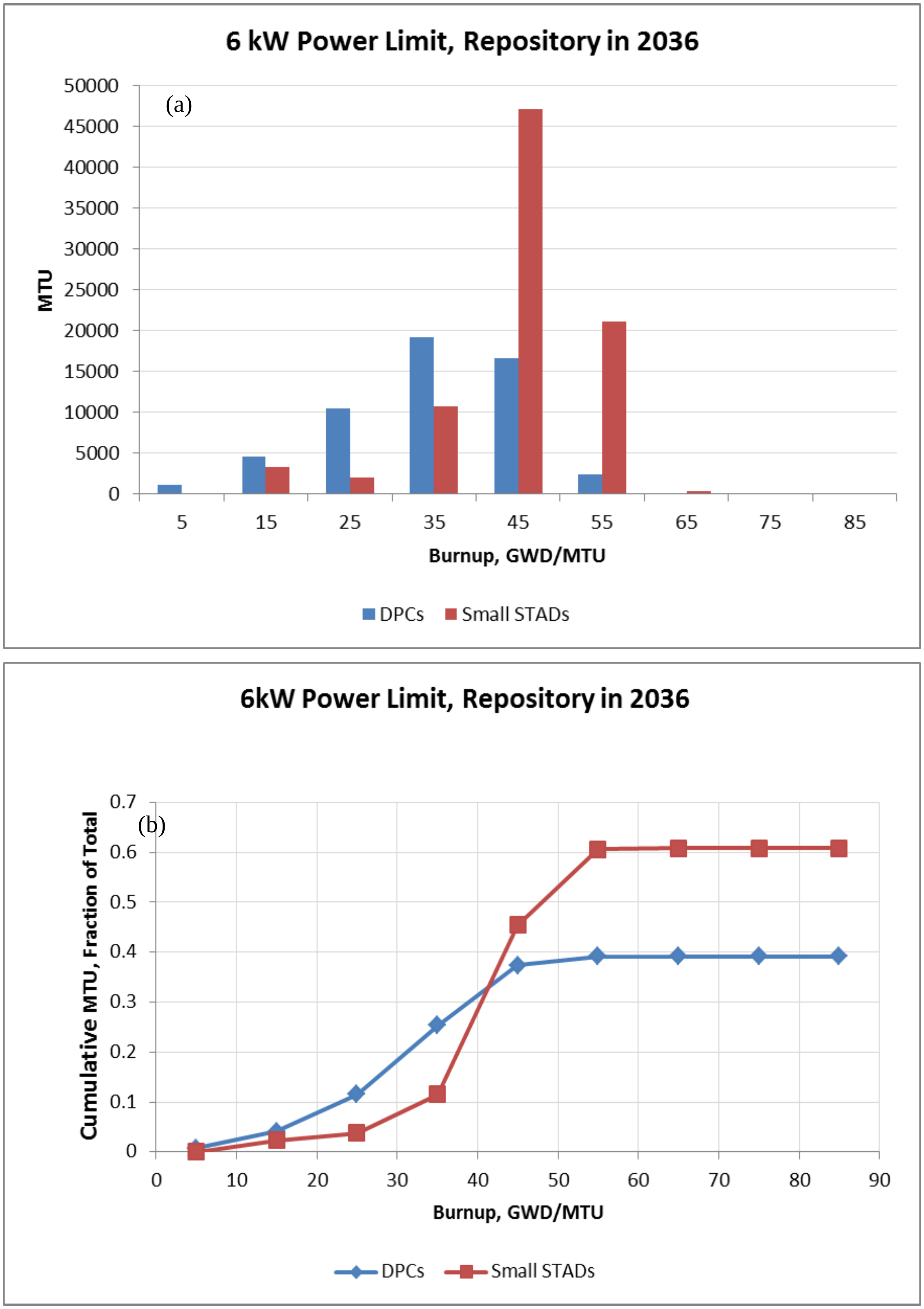


Figure 24. Burnup of Fuel in DPCs and STADs, 6 kW Thermal Power Limit, Repository in 2036.

4. CONCLUSIONS

The analysis presented in this report investigated how the direct disposal of DPCs may be affected by the use of STADs, early or late start of the repository, and the repository emplacement thermal power limits. The impacts were evaluated with regard to the availability of the DPCs and STADs for emplacement, achievable repository acceptance rates, additional storage required at ISF and additional emplacement time compared to the corresponding repackaging scenarios, and fuel age at emplacement. The conclusions of this analysis are summarized below.

Availability of DPCs and STADs for emplacement

For a repository start date of 2060, there is little difference in the availability of UNF for emplacement between the DPC-only loading scenario and the DPCs and STADs loading scenario, regardless of emplacement thermal power limit. This is because most of the UNF is in DPCs; only a small fraction of the UNF is in STADs as the use of STADs does not start until 2055.

Similarly, for an emplacement thermal power limit of 18 kW, there is little difference in the availability of UNF for emplacement between the DPC-only scenario and the DPCs and STADs loading scenario, regardless of repository start date. This is because the emplacement thermal power limit is high enough to accommodate DPCs without additional cooling time.

The biggest difference in the availability of UNF for emplacement between the DPC-only loading scenario and the DPCs and STADs loading scenario is for a repository start date of 2036 with a 6 kW thermal power limit. This is because relatively few of the DPCs can meet the thermal limit by 2036; additional time is required for the DPCs to cool sufficiently to meet the thermal limit. Because each STAD contains less UNF than does a DPC, it takes less time for the STADS to cool sufficiently to meet the thermal limit. In the same way, differences are also seen in the availability of UNF for emplacement between the DPC-only loading scenario and the DPCs and STADs loading scenario for the alternative with a 6 kW thermal limit and a 2048 start date, and for the alternatives with a 10 kW thermal limit and 2036 and 2048 start dates.

Additional Storage Capacity and Emplacement Time

In comparison to the reference repackaging case, the only alternatives requiring additional storage capacity were those in which UNF was disposed of in DPCs only. This was true for alternatives with both the 6 kW and 10 kW thermal limits with a repository start date in 2036 and for the alternative with the 6 kW thermal limit and a repository start date in 2048. In contrast, alternatives with disposal of UNF in both DPCs and STADs did not require additional storage, regardless of the repository acceptance rate, as compared to the reference repackaging case.

In comparison to the reference repackaging case, alternatives with the 18 kW emplacement thermal limit required little to no additional emplacement time, regardless of the repository start time, the fuel loading scenario, or the repository acceptance rate. Alternatives with the 10 kW emplacement thermal limit and the DPCs and STADs fuel loading scenario required some additional emplacement time, ranging from 0 to 19 years. Alternatives with the 10 kW emplacement thermal limit and the DPC-only fuel loading scenario required even more additional emplacement time, ranging from 5 to 45 years. All alternatives with the 6 kW emplacement thermal limit required the most additional emplacement time, ranging from 36 to 95 years.

In comparing the DPC-only fuel loading scenario and the DPC and STADs fuel loading scenario, the most significant decrease in additional emplacement time occurred in the alternative with the 6 kW thermal limit and the 2036 repository starting date, with a reduction of 43 years for both repository acceptance rates. With a reduction of 43 years, the additional emplacement time was 36 years for the 3,000 MTU/year emplacement rate and 52 years for the 4,500 MTU/year emplacement rate.

The earliest date at which repository operations ceased (2067) occurred in the alternatives with the 18 kW thermal limit with a repository opening date of 2036 and a maximum repository acceptance rate of 4,500 MTU/yr, regardless of the fuel loading scenario, as well in the alternative with the 10 kW thermal limit with a repository opening date of 2036 and a maximum repository acceptance rate of 4,500 MTU/yr with the DPCs and STADs fuel loading scenario. The latest date at which repository operations ceased (2162) occurred in the three alternatives with the 6 kW thermal limit and the use of DPCs only, regardless of repository starting date.

Fuel Age at Emplacement

The highest average age of fuel at emplacement is 88 years for the alternative with a 6 kW thermal limit, disposal of UNF in DPCs only, and a repository start date of 2060. The lowest average age of fuel at emplacement is 46 years for the alternative with a 6kW thermal limit, disposal of UNF in DPCs and STADs, and a repository start date of 2036. Compared to the DPC-only loading scenario, the use of DPCs and STADs decreases the average age of fuel at emplacement significantly for the alternatives with a 6 kW thermal limit and a repository start date of 2036 and 2048. In general, the difference in the average age of fuel at emplacement between the DPC-only and the DPCs and STADs fuel loading scenarios becomes less significant as the repository thermal limit increases and as the repository start date increases.

The highest maximum age of fuel at emplacement is 146 years for (1) the alternatives with a 6 kW thermal limit and disposal of UNF in DPCs only regardless of the repository start date and (2) for the alternative with a 10 kW thermal limit and disposal of UNF in DPCs and STADs and a repository start date of 2060. The lowest maximum age of fuel at emplacement is 81-85 years for the alternative with a 10 kW thermal limit, disposal of UNF in DPCs and STADs, and repository start date of 2036, and for the alternatives with a 18 kW thermal limit, disposal of UNF in DPCs only and DPCs and STADs, and a repository start date of 2036 and 2048. The difference in the maximum age of fuel at emplacement between the DPC-only and the DPCs and STADs fuel loading scenarios becomes less significant as the repository thermal limit increases and as the repository start date increases.

In general, the role of STADs is to store young high burnup fuel. For the alternative with a 6 kW thermal limit and the repository start date of 2036, 60% of the inventory is loaded in STADs. The majority of fuel in STADs is 30 years old or younger while the fuel in DPCs is 50 years old or older. The burnup of the fuel in STADs is mostly 45 GWD/MTU or higher while the burnup of the fuel in DPCs is mostly 35 to 45 GWD/MTU or lower.

Recommendations for Future Study

This analysis demonstrated that all the18 kW thermal power limit alternatives and 10 kW thermal power limit alternatives with small STADs are comparable to their corresponding repackaging scenarios, albeit with some additional emplacement time required for the 10 kW with STADs alternatives. This analysis also confirmed that the 6 kW thermal power limit alternatives with DPCs only will require additional storage capacity at ISF and additional emplacement time (for disposal beginning in 2036 and 2048).

However, implementing small STADs make these alternatives more comparable to the repackaging scenarios if the repository starts in 2036 or 2048.

The alternatives considered in this analysis should be further evaluated with regard to the detailed costs and the factors not considered in this analysis, such as worker dose, dose to members of the public, and economic benefits to host entities. Adding all the applicable criteria to the analysis will help reveal the important differences between the alternatives.

The logistic simulations are based on the assumption of the DPCs transportability and disposability. An additional analysis should be performed to evaluate this assumption and to provide an input for the next iteration of the direct disposal of DPCs study.

5. REFERENCES

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