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Scoping Calculation of the Impact of Increased Burnup Limits on Spent Fuel Pool Inventory Management

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ABSTRACT

Light water reactor (LWR) operators, fuel vendors, and regulators are working toward the use of advanced fuels (e.g., accident tolerant features, doped pellets, increased ^{235}U enrichment, and increased burnup). Increasing the burnup of the fuel increases the radiation source term and thus the decay heat. Under the assumption that dry storage decay heat loading limits remain constant, discharged higher burnup used fuel will require longer cooling times in the spent fuel pool (SFP), potentially increasing the population of fuel not yet ready for dry storage loading and thus impacting the total decay heat present in the SFP. Increased fuel assembly discharge burnup, given the same core power, will result in fewer assemblies discharged to the SFP, which will help alleviate the increase in population and total decay heat to some degree. This scoping calculation is intended to estimate the net effect of these two factors on SFP inventory: SFP heat load and dry storage system external dose rates. Several simplifying assumptions and approximations will be used to identify key considerations, determine expected trends, approximately quantify impacts, and illustrate the need to consider potential impacts when planning a transition to higher burnup cycle designs.

The results of this study estimate an increase in SFP inventory of approximately 0.3 to 0.8 full core equivalents, which is strongly dependent on the dry storage canister decay heat loading limits. Maximum decay heat in the SFP increases by 2% to 4% for HBU cases. Lastly, dry storage system external dose rates for normal cask loading activities will decrease, noting that fewer canister loadings will be needed in high-burnup cases.

Keywords

Decay heat
Discharge burnup
Dry storage
High burnup
Spent fuel pool

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1 INTRODUCTION

Light water reactor (LWR) operators, fuel vendors, and regulators are working toward the use of advanced fuels (e.g., accident tolerant features, doped pellets, increased ^{235}U enrichment, and increased burnup). Increasing the burnup of the fuel increases the radiation source term and thus the decay heat. Under the assumption that dry storage decay heat loading limits remain constant, discharged higher burnup fuel will require longer cooling time in the spent fuel pool (SFP), potentially increasing the population of fuel not yet ready for dry storage loading and thus impacting the total decay heat present in the SFP. Increased fuel assembly (FA) discharge burnup, given the same core power, will result in fewer assemblies discharged to the SFP, which will help alleviate the increase in population and total decay heat to some degree. This scoping calculation is intended to estimate the net effect of these two factors on SFP inventory: SFP heat load and dry storage system external dose rates. Several simplifying assumptions and approximations will be used to identify key considerations, determine expected trends, approximately quantify impacts, and illustrate the need to consider potential impacts when planning a transition to higher burnup cycle designs.

2 CURRENT U.S. LWR FUEL BURNUP LIMITS AND FUEL MANAGEMENT

Practical core design factors affecting the relationship between batch discharge burnup (DBU) and burnup limits are important considerations for the selection of enrichment and burnup combinations for decay heat and dose rate analyses. The current U.S. LWR fuel burnup limit is approximately 62 GWd/MTU[1] (gigawatt-days per metric ton of uranium) averaged over the fuel rod [1]. The U.S. LWR fleet has gradually increased fuel enrichment and DBU over the last several decades. Maximum rod-average burnups became a limiting factor for core designs in or around the early 2000s, leading to licensing actions to increase the limit to the current value to take advantage of enrichments up to 5 wt% ^{235}U [2].

Historical assembly enrichment and discharge burnup data for U.S. LWRs indicates that the average DBU for a 4 wt% ^{235}U assembly is 44 GWd/MTU [3]. In addition, the relationship between increased enrichment and increased DBU in the discharged fuel population has averaged about 11 GWd/MTU/wt%, leading to a projected DBU for 5 wt% fuel of 55 GWd/MTU. These are batch average estimates for the current fleet of pressurized water reactors (PWRs) and boiling water reactors (BWRs) over a broad range of time during which most operated on 18-month cycles. The relationship between batch average enrichment and batch average DBU varies with cycle length (e.g., 18 or 24-month cycles) and core specific power (MW/MTU), therefore, industry average values represent a mix of operating cycle lengths and may differ for a particular reactor [3].

Due to the practicalities of core design, batch average DBU must be substantially lower than maximum assembly average burnup and even lower than the peak rod burnup limit. There are burnup variations among assemblies in a batch (~13% maximum assembly / batch average is typical) [3]. In addition, variations of pin burnup within each assembly (the peak rod is at least a few percent higher than average), and the necessity of allowing some cycle design margin for prediction uncertainty as well as uncertainty in the current and future cycle load factors (a few percent) results in a maximum assembly DBU typically 8% less than the peak rod burnup limit [3]. These factors mean that the approximate upper limit on batch DBU is about 20% lower than the peak rod limit, roughly 50 GWd/MTU for the current 62 GWd/MTU limit. Fuel enrichments of 5 wt% or less are sufficient to achieve this batch average DBU in 18-month PWR cycles and 24-month BWR cycles.

Annual fuel discharge data compiled by the U.S. Energy Information Administration (EIA) [4] shown in Figure 1 indicates that average DBU for the U.S. fleet reached a maximum of about 47 GWd/MTU in the mid-2000s and has remained range-bound since. This maximum is about 3 GWd/MTU less than the hypothetical 50 GWd/MTU limit, possibly due to a combination of conservative design practices and lower than maximum cycle capacity factors.

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[1] The 62 GWd/MTU limit varies slightly amongst fuel vendors.

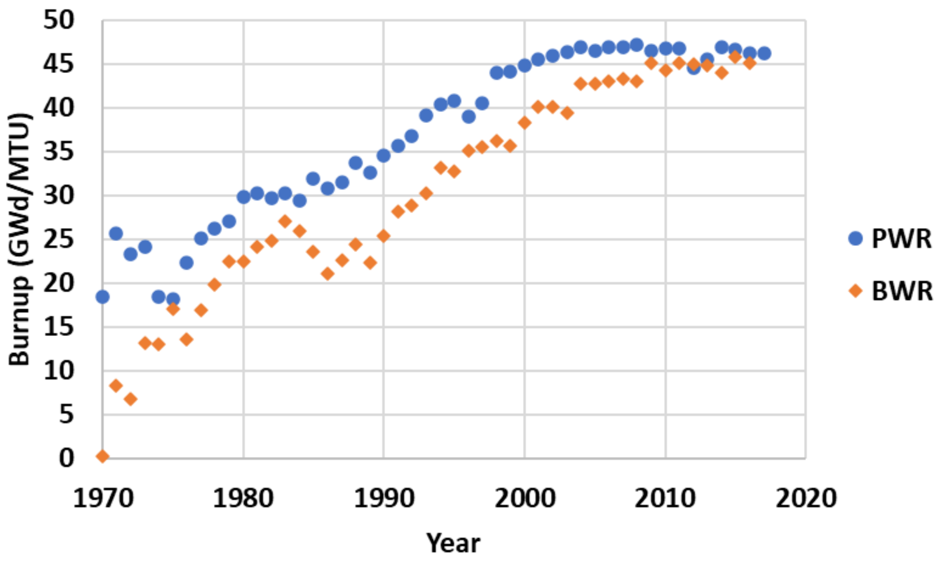

Figure 1. U.S. EIA annual average discharge burnup data

3 APPROXIMATE PWR FUEL LOADINGS AND DBU FOR 62 AND 75 GWD/MTU PEAK ROD BURNUP LIMITS

To approximate the effect of higher enrichment and DBU on SFP used fuel inventory and migration to dry storage, three "typical" PWR cases will be considered. The base case (i.e., case 1) is a standard 18-month cycle with a 62 GWd/MTU peak rod burnup limit and is meant to be representative of a modern PWR cycle. The second case increases the peak rod burnup limit from 62 to 75 GWd/MTU. The third case has the same increased burnup limit as case 2 but also extends the cycle length to 24 months. For all three cases, a core specific power of 39.3 MW/MTU and an arbitrary core size of 100 assemblies is selected. Modeled cycles assume two sub-batches per reload with the maximum sub-batch burnup assumed to be up to 9% higher than the batch average discharge burnup limit. An assumed capacity factor of 98% is used for all cases. The capacity factor and outage lengths are aggressive and consistent with base-load operation. The batch average DBU limits are set at 80% of the peak rod burnup limit, consistent with the prior section. Table 1 shows the batch average and maximum sub-batch DBU limits used to determine enrichment and batch sizes for the three cases.

Table 1. Case matrix

Case	Case Name	Peak Rod Burnup (GWd/MTU)	Cycle Length (months)	Outage Duration (days)	Batch DBU Limit (GWd/MTU)	Max Sub-Batch DBU (GWd/MTU)
1	Base	62	18	20	50	54.5
2	18-Month HBU	75	18	20	60	65.4
3	24-Month HBU	75	24	23	60	65.4

Equilibrium cycle batch average enrichment and sub-batch burnups are approximated using the "cycle estimator" [3], which has been validated for PWRs by comparison to GC-859 [5] enrichment and burnup data as well as two published 24-month cycle transition studies. Enrichments are batch average, which averages in reduced enrichment blanket regions and differing sub-batch (high and low) enrichments. For this scoping work, second order effects on fuel efficiency, such as burnable absorber type or fuel lattice design are ignored because the purpose of this effort is to estimate the effect of a transition to HBU using the same design. Cycle estimator results for the three cycle design cases are shown in Table 2.

Table 2. Fuel batch enrichment and burnup information for the three cycle design cases

Case	Enrichment (wt%)	Sub-Batch 1 Assemblies	Sub-Batch 1 DBU (GWd/MTU)	Sub-Batch 2 Assemblies	Sub-Batch 2 DBU (GWd/MTU)	Batch Average DBU (GWd/MTU)
1	4.4	26	45.3	16	53.3	48.3
2	5.1	2	47.8	32	60.5	59.8
3	5.4	41	56.9	6	64.9	57.9

Case 1 uses a 42% reload batch fraction. The average DBU is limited to 48.3 GWd/MTU by the sub-batch 2 burnup. The batch average enrichment estimate of 4.4 wt% is consistent with the GC-859 data (44 GWd/MTU at 4.0 wt% and 11 GWd/MTU/wt% trend). Case 2 uses just over a 1/3 core reload batch size to obtain approximately 59.8 GWd/MTU average DBU. Use of a smaller batch size with higher enrichment would require a 4th cycle for some fuel, likely exceeding the sub-batch limit. Case 3 uses a 47% reload batch fraction, and results in a 57.9 GWd/MTU batch average DBU. This batch size is required to maintain the sub-batch 2 burnup below the limit[2]. Each case assumes that re-use fuel burnup is equal to the batch average burnup at the end of the prior cycle. This is an approximation; core designers typically choose assemblies for use in the final cycle from the lower burnup assemblies in the batch. However, for this evaluation, the same simplifying assumptions are made for each case for consistency.

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[2] Note that the 64.9 GWd/MTU sub-batch is small (only 6 assemblies), and thus it can be assumed that the burnup variation within the sub-batch is smaller than the 13% described previously for the batch. Therefore, the peak rod burnup will remain below the 75 GWd/MTU limit.

4 DISCHARGED ASSEMBLY DECAY HEAT AND SFP INVENTORY

Discharged sub-batch decay heat is estimated for a typical 17×17 PWR fuel assembly (0.47 MTU/assembly) depleted at constant core-average power (39.3 MW/MTU) using ORIGEN-generated data that spanned three enrichments (4.4%, 5.1%, and 5.4%), five burnups (15, 30, 45, 60, and 75 GWd/MTU), and 33 state points ranging from very short decay times (<0.01 years) to greater than 40 years [6]. The ORIGEN calculations which generated these data utilized libraries that are specific to PWR 17×17 lattice designs, span enrichments from 3 wt% to 8 wt%, and span burnups up to 90 GWd/MTU. A portion of the 4.4 wt% data is shown in Figure 2. For this scoping work, neither outages between cycles nor variations in cycle average power for different cycles were modeled. Modeling these effects would likely reduce decay heat estimates, however, for consistency each cycle type analyzed uses the same power history assumptions.

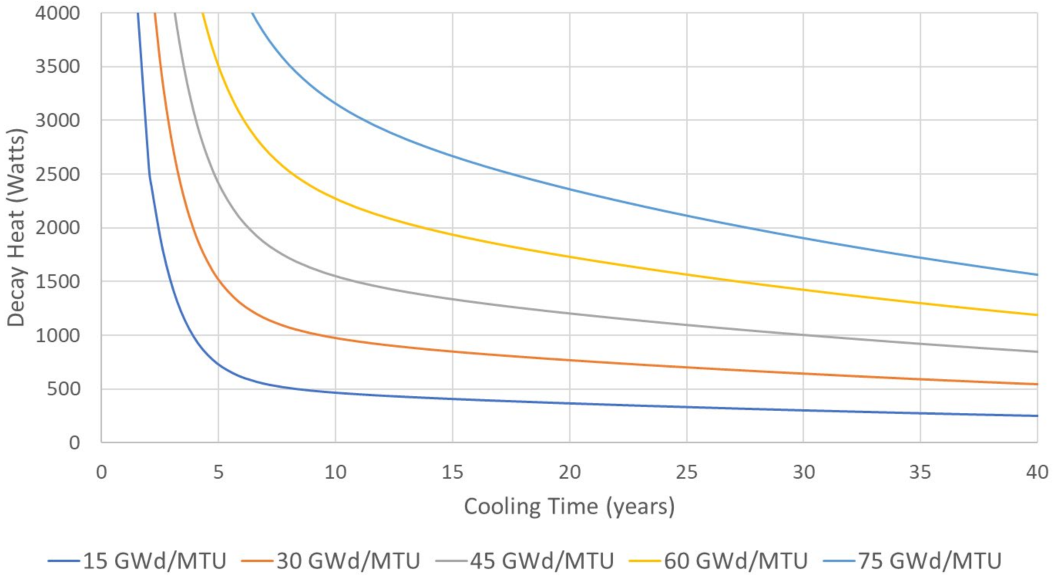

Figure 2. Decay heat data for fuel with 4.4% ^{235}U enrichment

Figure 3 illustrates one additional trade-off that is important for decay heat and dose rate evaluations. Increased burnup is achieved by increasing enrichment. Although burnup increases decay heat, enrichment reduces decay heat, particularly in the decay times of interest for SFP storage and movement of used fuel to dry storage. For these analyses, it is important to use realistic combinations of enrichment and burnup.

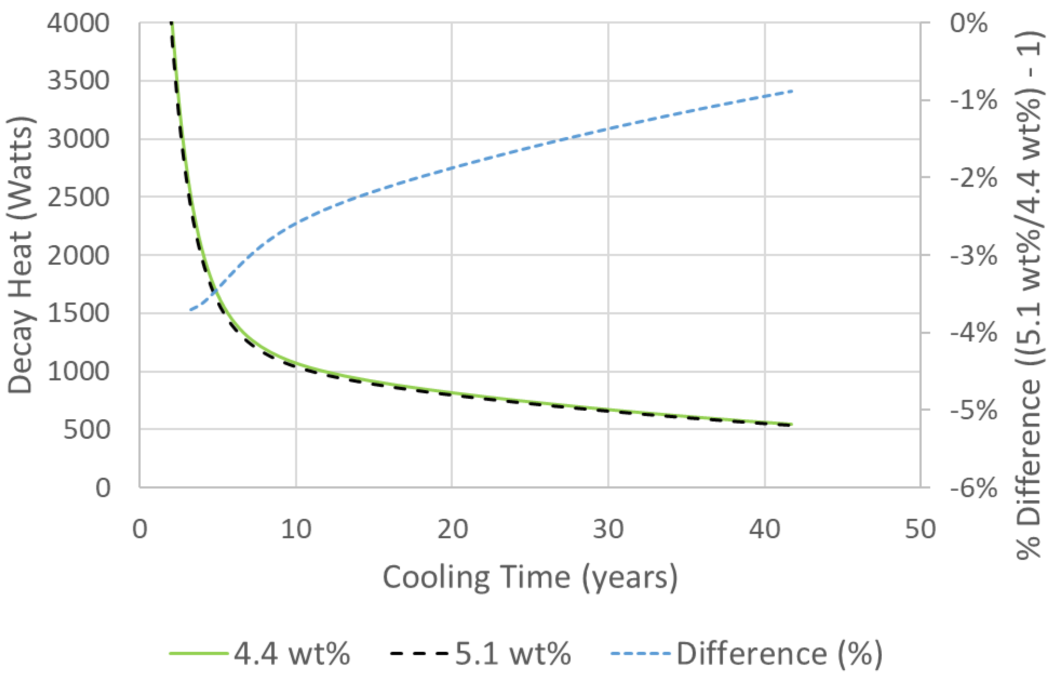

Figure 3. Decay heat comparison for two different enrichment levels for a DBU of 60 GWd/MTU

Using data from Figure 2, Figure 4 shows the cooling time required to reach the same decay heat with different fuel burnups. For current levels of batch average DBU (~45 GWd/MTU), cooling time increases modestly (~3 years) if the target decay heat is reduced from 2000 W to 1000 W. At 60 GWd/MTU (33% higher burnup), the decay time increases by approximately 8 years (a 267% larger increase). Therefore, as burnup increases, the decay heat limit of the dry storage system becomes more important for the net effect of tradeoff between fewer assemblies discharged and greater required cooling time.

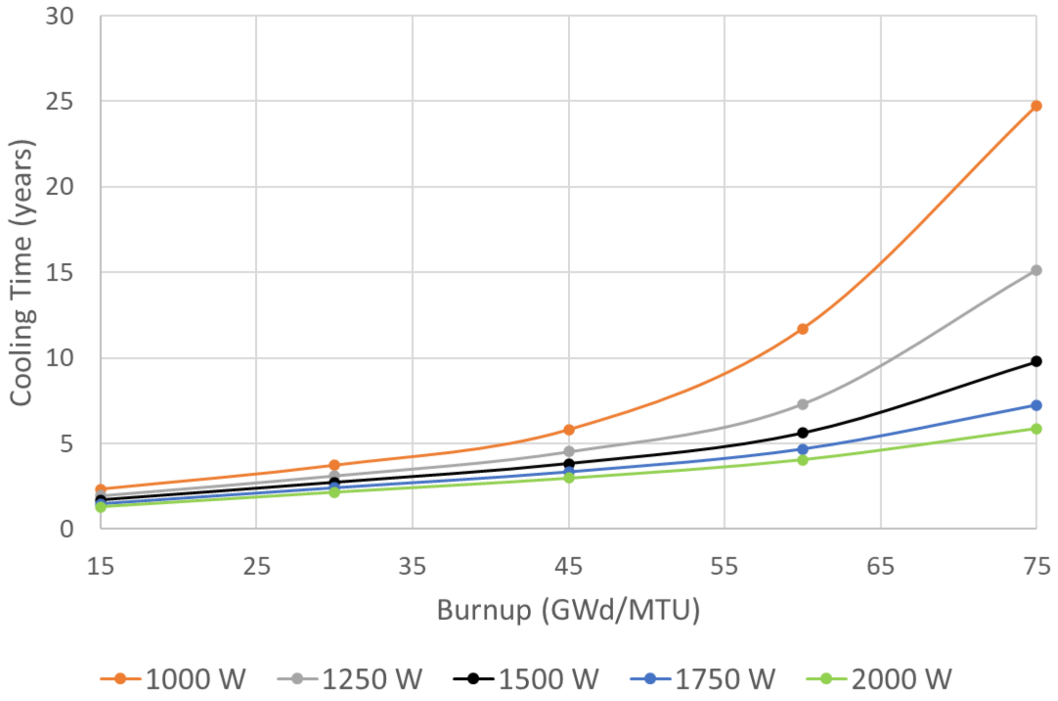

Figure 4. Cooling time needed to achieve specific decay heat values as a function of burnup

5 FUEL ASSEMBLY QUALIFICATION AND STRANDED ASSEMBLIES

For each sub-batch DBU in the SFP inventory management evaluations, the assembled decay heat data described in this section is cubic spline-interpolated on burnup (15, 30, 45, 60, and 75 GWd/MTU) and cubic spline-interpolated on decay time. Required decay times (years) for the sub-batches of the base case (4.4 wt%) and the 18-month HBU case (5.1 wt%) for an assumed uniform canister decay heat limit of 1149 W are shown in Table 3. The decay heat limit is reduced by 5% for the decay heat calculation to account for uncertainty in fuel burnup and decay heat prior to the interpolation.

Table 3. Decay times for select DBU values

	Base Case (18-Month)		HBU Case (18-Month)	
Burnup (GWd/MTU)	45.3	53.3	47.8	60.5
Decay Time (Years)	5.3	7.0	5.5	9.2

For the equilibrium SFP population calculation, multiple cycles of sub-batch discharges are tabulated. The SFP population of "stranded" assemblies is calculated by determining the number of assemblies in each batch of each completed cycle that cannot yet be loaded into dry storage due to insufficient cooling time. Canister loading is assumed to occur mid-cycle (halfway between refueling outages). Some assemblies from a particular cycle may qualify for a canister zone while other assemblies do not, resulting in a partially loaded canister for fuel from that cycle. It is assumed that partially loaded canisters are filled with fuel from older cycles that are available in the spent fuel pool. Thus, all assemblies that meet the decay heat requirement will be loaded into dry storage. The calculation does not account for fuel already in the pool prior to the operation of base case cycles or HBU cycles. Of interest here is the equilibrium number of assemblies that cannot be loaded due to insufficient cooling time.

At equilibrium, for each new cycle, none of the newly discharged assemblies would qualify for canister loading, but an equal number of previously discharged assemblies would become newly qualified. This simplified stranded assembly calculation only considers decay heat limits and is not intended to represent the assembly selection process for actual canister loadings. Rather, it is a consistently applied method intended to illustrate and approximate the change in the stranded assembly population when transitioning to a 75 GWd/MTU peak rod burnup limit.

6 DRY STORAGE CANISTER DECAY HEAT LIMIT EVALUATION

For each of the three cycle design cases, three different dry storage canister decay heat limit sets are evaluated. These are shown in Table 4 and represent a reasonable range of modern canister decay heat limits. The total decay heat shown assumes 37 assemblies per canister.

Table 4. Canister loading limits

Canister	Zone 1 Limit (W/FA)	Zone 1 Fraction	Zone 2 Limit (W/FA)	Zone 2 Fraction	Zone 3 Limit (W/FA)	Zone 3 Fraction	Total Decay Heat (kW)
1 (Uniform)	1149	1.0	N/A	N/A	N/A	N/A	42.5
2 (3 zones) [7]	1000	0.351	1313	0.432	2000	0.216	50.0
3 (3 zones) [8][3]	1215	0.432	1080	0.243	1080	0.324	42.1

The SFP-to-canister decay heat evaluations have two goals:

1. Determine the effect of HBU cycles on the population of discharged fuel in the SFP that has not cooled enough to be loaded into dry storage (stranded assemblies).
2. Determine the effect of HBU cycles on the maximum decay heat in the SFP.

The metric for the first goal is the difference in the number of stranded assemblies in units of full core equivalents between the HBU cycles and the base case (i.e., the equilibrium number of HBU cycle stranded assemblies minus the equilibrium number of base cycle stranded assemblies divided by the core size). The metric for the second goal is the % change in maximum SFP decay heat (considering only stranded assemblies and the full core offload). SFP decay heat peaks at the end of a full core offload, when the offloaded core decay heat is added to the stranded assembly decay heat. The offloaded core decay heat is a weak function of burnup and enrichment and depends mostly on the power of the assemblies during operation. Thus, the offloaded core decay heat only varies by a few percent for each case since the core power is constant for all three cases. Because of this weak dependency on burnup, the offload decay heat is estimated using the core average burnup and enrichment from the cycle estimator and the decay heat is evaluated after 140 hours of cooling time (approximate time of the end of core offload after shutdown of the prior cycle). The SFP population and peak decay heat for each of the 3 cases are calculated assuming that long term equilibrium has been established.

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[3] These limits represent 90% of the Pattern B limits from Table 1.2.3(b) in Reference 8. Pattern B was selected because it was superior to Pattern A for this scoping study and 90% was selected to make it generally more applicable to helium dehydration and vacuum drying.

For the uniform loading case, the change in the stranded assembly population can be calculated as a function of the uniform loading decay heat limit. For this evaluation, it is assumed that the canister size is equal to the discharge batch size for each case.

Results of the SFP inventory change calculation are shown in Figure 5. With a dry storage decay heat limit of 700 W, approximately 1.6 to 2.1 cores of SFP space are required to accommodate the HBU cycles, with the 18-month HBU cycle case requiring more space than the 24-month case. However, at 1500 W, there is essentially no storage penalty for either HBU cycle. Between 700 W and 1500 W the space requirement declines generally in stairstep fashion, and the average decay heat limit for current generation canisters is also in between these two values.

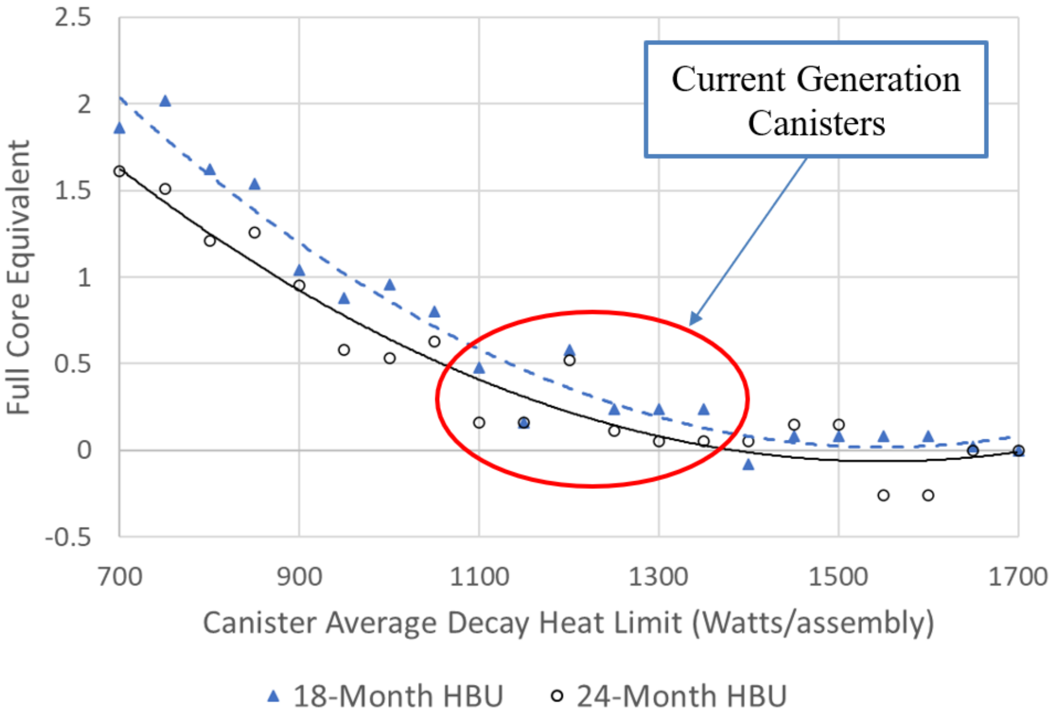

Figure 5. Extra SFP storage needed for the HBU cycles compared to the non-HBU 18-month base case (case 1)

The change in stranded assembly population for each HBU cycle case (Table 1) and canister limit (Table 4) combination is shown in Table 5. Values are given in units of full core discharges.

Table 5. Change in stranded assembly population for the HBU cases compared to the non-HBU 18-month base case (i.e., case 1)

Canister	Loading	18 Month HBU	24 Month HBU
1	Uniform	0.2	0.2
2	Zoned	0.6	0.3
3	Zoned	0.5	0.2

Results are dependent on HBU transition strategy (18- or 24-month cycles) and canister zoning decay heat limits and range from 0.2 to 0.6 full core discharges. The 24-month cycle HBU case additional space is smaller than the 18-month cycle HBU case and appears to be manageable. These evaluations were also performed using core sizes of 157 and 193 assemblies and a fixed canister size of 37 assemblies to verify the methodology with more realistic values, and to ensure the assumption of the canister size being equivalent to the batch size is not significantly biasing the result. Since the batch size is larger than the canister size when using this assumption, multiple canisters need to be loaded in some loading campaigns. For cycles in which multiple canisters are loaded, it is assumed that only one of those canisters includes assemblies that already existed in the SFP and were not part of the discharged population for the cycles analyzed. The results for both the 157 and 193 assembly cores show an increase of approximately 0.2 for canister 2 and less than 0.1 for canister 3 for both the 18-month and 24-month HBU cases. Note that this difference is mostly attributed to the fixed canister size assumption[4].

Maximum SFP decay heat changes are shown in Table 6. Across all cases, the increase in SFP peak decay heat ranges from 2% to 4%. For the 157 and 193 assembly cores, the increase is no greater than 0.4% for canister 2, and no greater than 0.2% for canister 3.

Table 6. Maximum decay heat changes for the HBU cases compared to the non-HBU 18-month case (case 1)

Canister	Loading	18 Month HBU	24 Month HBU
1	Uniform	2.7%	2.4%
2	Zoned	3.4%	2.7%
3	Zoned	3.3%	2.5%

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[4] If the assumption that the canister size equals the discharge batch size is applied to the 157 and 193 assembly cases, the deviation in the number of full cores is less than 0.1.

7 ESTIMATED IMPACT ON DRY STORAGE DOSE RATES

Dry storage system neutron and gamma dose rates are dependent on the amount and type of shielding and on the strength of the used fuel neutron and gamma sources. Neutrons in used fuel come primarily from actinides, while fission products are the majority contributors for gammas within the burnup range of this assessment [9]. Fission products in total tend to build up linearly with burnup, while actinides require one or more successive neutron absorptions and as a group increase more than linearly with burnup. Further, increasing enrichment has little effect on total fission product inventory but can reduce actinide production significantly. As with decay heat, it is important to use realistic enrichment/burnup combinations, particularly for neutron dose rate calculations.

Storage, transfer, and transport cask dose rates have been previously calculated for various used fuel enrichment and burnup combinations [9]. These calculations assume a uniform thermal loading of 1200 W/assembly and evaluate dose rates at both normal conditions (storage, transport) and hypothetical accident conditions (transfer). Although the burnup and enrichment combinations used are not fully consistent with those used in this report, dose rate results of the study are useful. In addition, the accident condition is modeled very conservatively and assumes no neutron shielding and may not be representative of an actual licensing calculation. It is used herein only as a neutron dose rate-dominated example case for comparison between base loading and HBU loading.

Figure 6 compares the enrichment and burnup combinations used in Reference 9 with the batch average values from the three cycle scenarios in this study. In Reference 9, burnup was increased 9 GWd/MTU for a 1 wt% increase in enrichment, which is reasonably close to the 9.6 GWd/MTU/wt% increase for the change from the 18-month cycle base case to the 24-month-cycle HBU case.

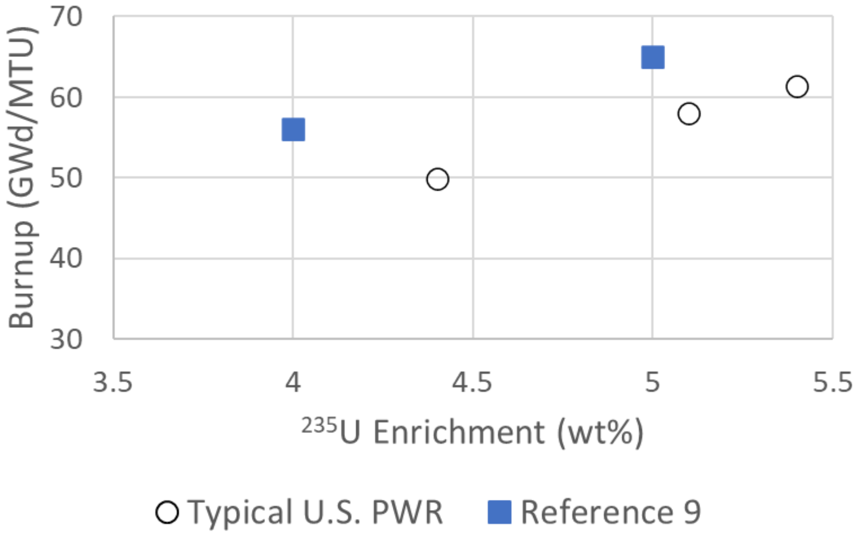

Figure 6. PWR enrichment and discharge burnup case comparison

Figure 7 is a reproduction of data from Figure 13 of Reference 9 which shows dose rate results for a dry storage canister in a concrete overpack in normal storage conditions. Dose rates from this configuration are from gamma sources, due to the neutron shielding effect of the concrete overpack. The external dose rate declines with increased burnup because the additional cooling time required by higher burnup fuel to meet decay heat limits reduces the gamma source term below that of the lower burnup / lower cooling time fuel.

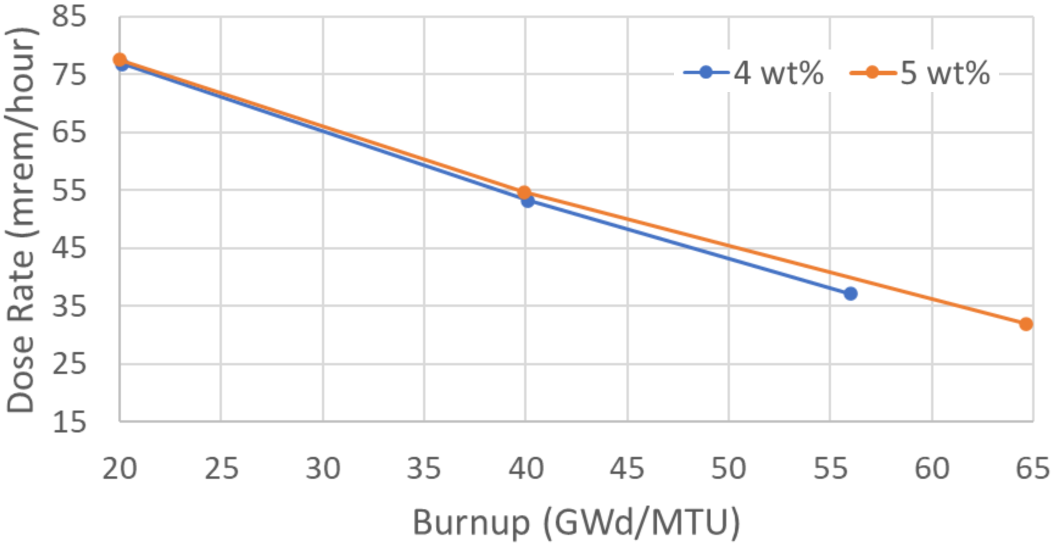

Figure 7. Dose rate versus burnup for a storage cask (courtesy of Oak Ridge National Laboratory) [9]

Figure 8 is also a reproduction of data from Figure 13 of Reference 9 which shows dose rate results for a transfer cask in accident conditions, in which the water neutron shield is modeled as air. In this neutron dominated configuration, the calculated dose rates of the 56 GWd/MTU and 65 GWd/MMTU cases are approximately equal.

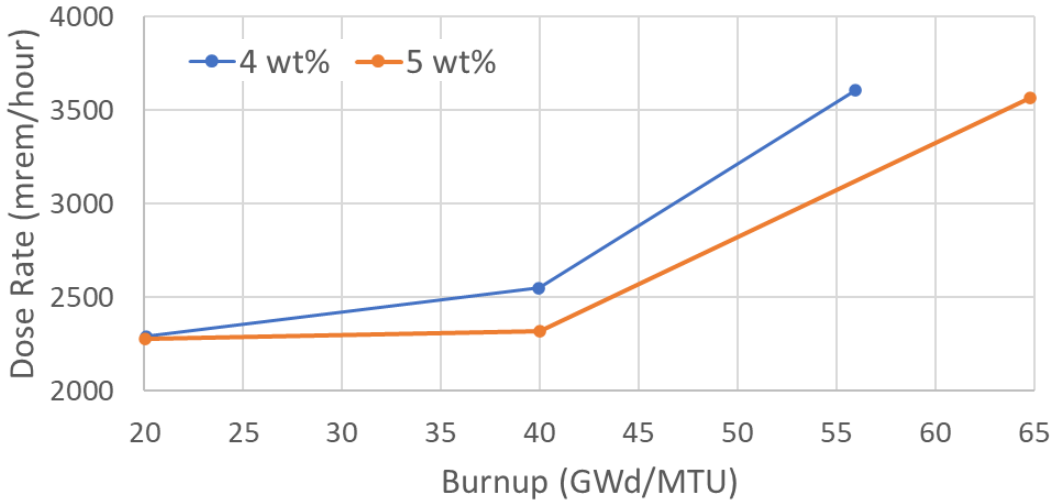

Figure 8. Dose rate versus burnup for a transfer cask (courtesy of Oak Ridge National Laboratory) [9]

Considering that the number of dry storage canisters would be reduced by 14% for the 65 GWd/MTU case relative to the 56 GWd/MTU case, based on the ORNL results, cumulative dry storage related dose from normal and accident conditions would be lower at the higher burnup.

As a confirmation of this result, the EPRI Cask Loader software [10] was used to assess the normal dry storage case using the following input:

- 18-month base case, 2 sub-batches, Table 2 enrichment and burnup
- 24-month HBU case, 2 sub-batches, Table 2 enrichment and burnup
- Uniform canister loading, 1100 W per assembly
- Independent calculation of decay time

The small neutron contribution increased 26%, but the much larger gamma contribution declined 10%, leading to an overall reduction of 9%. In addition, cumulative doses would be further reduced due to fewer canister loadings (16% fewer in the 24-month cycle case).

8 CONCLUSIONS

Scoping calculations were performed to evaluate the SFP inventory and decay heat effects of a transition from current cycles designs based on a 62 GWd/MTU peak rod burnup limit to 18- or 24-month HBU cycles based on a 75 GWd/MTU peak rod burnup limit. Realistic PWR enrichment, discharge burnup, and reload batch sizes were used. The SFP fuel assembly inventory of “stranded” fuel (fuel with too much decay heat for dry storage loading) is estimated to increase by about 0.3 to 0.8 full core equivalents and depends strongly on the dry storage canister decay heat loading limits. Maximum decay heat in the SFP increases by 2% to 4% for HBU cases.

An additional high-level assessment of dry storage system external dose rates suggests that normal storage per-canister and cumulative dose rates will decline for HBU cycles, noting that HBU cases require fewer canister loadings. Neutron-dominated accident condition dose rates for HBU cases are not expected to change substantially but could be moderately higher or lower due to a strong dependence on actinide content. Actinide content is a strong function of burnup and enrichment, highlighting the need to use realistic combinations of burnup and enrichment, particularly for dose rate assessments.

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