Proceedings of the 18th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2016
September 18-23, 2016, Kobe, Japan

Paper No. 2050

Study of Axial Burnup Profile Effects on BWR Burnup Credit*

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Abstract

Oak Ridge National Laboratory and the United States Nuclear Regulatory Commission have initiated a multiyear project to investigate the application of burnup credit for boiling-water reactor (BWR) fuel in storage and transportation systems. Many aspects of burnup credit must be considered if credit for burnup beyond peak reactivity can be accepted. This paper presents the results of a study examining the effect of axial burnup profiles on calculated cask reactivity for discharged BWR fuel assemblies.

The axial burnup profiles used in this study are normalized end of cycle (EOC) profiles taken from a single cycle of operation at a modern BWR. This set of profiles was selected because it is from the same detailed operational data set used for other aspects of the overall project examining BWR burnup credit. A total of 624 profiles are available from a range of fuel assembly design types, and the EOC burnups range from 16.8 to 48.5 GWd/MTU. The profiles provide sufficient breadth to assess the generic impacts of axial burnup profiles on discharged fuel assembly reactivity.

Cask reactivity is determined in the GBC-68 calculational benchmark model assuming a loading of 68 GE-14 assemblies with the same discharged burnup and axial burnup profile. The calculations are repeated assuming discharged burnups of 30, 40, and 50 GWd/MTU; and each of the 624 profiles is considered at each discharge burnup. The calculations are also performed both neglecting the presence of natural-enrichment axial blankets (a common practice in pressurized-water reactor burnup credit) and crediting the presence of these blankets. The trends are generally consistent at all burnups, both with and without axial blankets, although the overall reactivity level is much lower

* This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

with explicit blanket modeling. Overall assembly reactivity is controlled by the reactivity of the top few nodes in the assembly, and it is noted that a larger number of top nodes is important when the blankets are modeled. The resulting k_{eff} values cover a broad range, indicating a strong dependence of discharged assembly reactivity on axial burnup profile. End effects as high as 12.7 % Δk are also noted. These results indicate that while the effects of axial burnup profiles on BWR burnup credit are similar to effects on pressurized-water reactor burnup credit, the reactivity impacts are larger. Appropriate axial burnup profile selection is essential for a conservative BWR burnup credit analysis beyond peak reactivity.

Introduction

Oak Ridge National Laboratory (ORNL) and the United States Nuclear Regulatory Commission have initiated a multiyear project to investigate the application of burnup credit (BUC) for boiling-water reactor (BWR) fuel in storage and transportation systems (often referred to as casks) and spent fuel pools (SFPs). This work is divided into two main phases. The first phase investigated the applicability of peak reactivity methods currently used in SFPs to casks and examined the validation of reactivity calculations and depleted number densities within these methods. The results of the first phase investigations have been published in Marshall et al. [1]. The second phase is focused on extending BUC beyond peak reactivity. This paper documents early second phase work performed to determine the impacts of axial burnup profiles on cask reactivity at a range of burnups beyond peak reactivity. This paper provides a more complete discussion of this topic than a previous paper [2], which was primarily focused on axial void fraction and control blade history effects.

This paper presents a summary of the codes and models used in this work. The summary is followed by a description of the set of burnup profiles used, as well as the results of calculations based on modeling approaches with and without natural-enrichment axial blankets. Finally, a summary and conclusions are presented.

Codes Used

BUC analyses require the use of a series of codes and models to simulate fuel depletion in the core and spent nuclear fuel (SNF) reactivity in the storage and transportation system. The SCALE code system [3], version 6.1.3, was used for all calculations in this work.

STARBUCS

The STARBUCS sequence provides an automated link between ORIGEN-ARP depletion calculations and CSAS criticality safety calculations. STARBUCS creates depleted fuel compositions based on pregenerated ORIGEN libraries, a fresh fuel description, and an input irradiation history. The sequence performs a depletion and decay calculation for each axial node in the cask model using the ORIGEN-ARP methodology and generates a material composition that can be directly entered into KENO. All STARBUCS calculations performed in this report use SCALE 6.1.3 [3].

The ORIGEN-ARP methodology performs ORIGEN depletion calculations using cross section libraries pregenerated for specific fuel assembly lattice configurations as a function of burnup, and for discrete values of parameters characterizing these configurations (e.g., enrichment, moderator density). In this case, the configurations are the full lattice present in the lower portion of the fuel assembly, and the vanished lattice present in its upper portion. The pregenerated cross sections are interpolated using the ARP code over a range of varying fuel assembly properties, including burnup and moderator density. The interpolation scheme retains the accuracy of the explicit TRITON calculations used to pregenerate the cross section libraries.

A limitation of STARBUCS is that it can use only a single ORIGEN library in a calculation. Since the GE14 assembly design type examined in this work was modeled with two lattices, two STARBUCS calculations were needed to determine depleted compositions for the entire assembly. The compositions from the individual depletion calculations were combined to make a single set of compositions representing the depleted and decayed fuel compositions in each KENO calculation.

KENO

The Criticality Safety Analysis Sequence (CSAS)/KENO performed reactivity calculations for the GBC-68 computational benchmark model [4]. The sequence provides automated problem-dependent cross section processing followed by 3-dimensional (3D) multigroup Monte Carlo neutron transport calculations to solve the k_{eff} eigenvalue problem. All calculations were performed using the 238-group neutron cross section library based on ENDF/B-VII.0 data. All KENO calculations performed in this report used SCALE 6.1.3 [3].

Two different sets of nuclides can be used for fuel modeling in the CSAS models: (1) major actinides only (AO) and (2) major and minor actinides and major fission products (AFP). The nuclides used in the AO and AFP nuclide sets were taken from NUREG/CR-7109 [5] and were the same as those typically used in calculating pressurized-water reactor (PWR) BUC. The same isotope sets are appropriate for use in BWR BUC because the same nuclides result from fission in both types of light water reactors. Table 1 provides the BUC nuclides considered in the AO and AFP sets. Gadolinium-155 is included in the AFP set, but ^{157}Gd is not. At typical discharge burnups, there is almost no ^{157}Gd remaining from the initial burnable absorber loading so neglecting this isotope is not a large reactivity penalty.

Table 1 AO and AFP isotope sets

10 AO isotopes									
^{234}U	^{235}U	^{238}U	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am	^{16}O
29 major and minor actinides and major fission products (AFPs)									
^{234}U	^{235}U	^{236}U	^{238}U	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
^{241}Am	^{243}Am	^{95}Mo	^{99}Tc	^{101}Ru	^{103}Rh	^{109}Ag	^{133}Cs	^{147}Sm	^{149}Sm
^{150}Sm	^{151}Sm	^{152}Sm	^{143}Nd	^{145}Nd	^{151}Eu	^{153}Eu	^{155}Gd	^{16}O	

Characteristics of Profiles Used

Initially, a set of profiles had to be generated, as no BWR database analogous to the PWR database used in Wagner, DeHart, and Parks [6] currently exists. The set of profiles generated for this work were the normalized end of cycle (EOC) axial burnup profiles for all 624 assemblies in a proprietary core follow data set. The BWR profile set generated is more limited than the PWR database but was sufficient for use in this study. The axial burnup profiles were used to generate a range of cask k_{eff} values at multiple burnups for each of the profiles considered, including both the AO and AFP isotope sets. Analysis of the calculation results is presented, including the range of k_{eff} values that resulted from the profiles considered, the magnitude of the end effect associated with the profiles, and a brief examination of the effect on the cask k_{eff} of the discharge burnup of the assembly from which each profile was taken. This analysis was performed both for models that neglect the presence of natural enrichment blankets and for models that include these blanket regions.

Most of the BWR SNF in the United States domestic inventory has reduced-enrichment (typically natural) blankets. A routine modeling simplification made in PWR BUC is that no blankets are present, and this assumption is conservative because it significantly increases the quantity of fissile material in the relatively high-reactivity ends of the assembly. The assembly ends have high reactivity because they have low burnup; this effect was studied extensively for PWR SNF in Wagner, DeHart, and Parks [6]. The examination of the effects of BWR axial burnup profiles thus started with the same modeling simplification: that the axial blankets are not present in the discharged fuel assemblies. This simplification also provided a basis for a comparison of the results of this study with those generally established for PWR axial burnup profile effects in [6]. The profiles used in this study were generated by a 3D core simulator model that appropriately represented the fuel as manufactured, (i.e., with blankets), but the GBC-68 cask model introduced a modeling simplification of full-enrichment (4.5 wt% ^{235}U) fuel over the entire length of the assembly. The examination of axial burnup profile effects was subsequently extended to include explicit modeling of the blankets with the as-built natural enrichment. This further study allowed for a quantification of the margin introduced by neglecting blankets and a comparison of limiting profiles in both blanketed and unblanketed models.

The EOC burnup profiles generated for all 624 assemblies in the core follow data set were normalized to the assembly average burnup to enable comparisons among profiles independent of the burnup of the assembly from which the profile was taken. Representative profiles from relatively high-burnup assemblies are shown in Figure 1. The top of the assembly corresponds to low node numbers, i.e., node 1 is at the top of the assembly and node 25 is at the bottom. There are two profiles that show a more bottom-skewed burnup profile than the others, shown with a solid green line and a solid purple line. Another four profiles have a feature at the top end of the assembly (low node number). This feature, hereinafter referred to as the *hockey stick*, is present for many more profiles and is related to a longer top axial blanket. Most fuel assemblies, 568 of the 624, had 6 in. top and bottom natural-enrichment blankets. The remaining 56 profiles had a 12 in. long natural blanket, which resulted in the lower relative burnup in node 2 compared with the other profiles. Even considering the hockey stick feature, the variability among profiles was less for the intermediate-burnup profiles than for the low-burnup profiles. The range of relative burnups at node 5 for profiles shown in Figure 1 was approximately 0.15, representing 83% of the variation seen in the intermediate-range profiles and a 50% reduction relative to the low-burnup profiles at the same elevation.

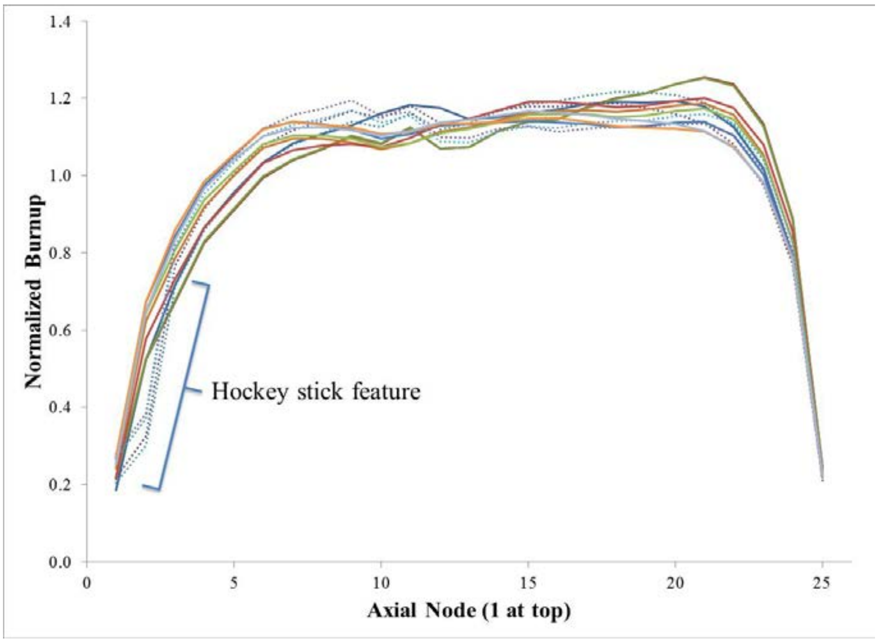

Figure 1 Selected normalized burnup profiles from assemblies with EOC burnups greater than 40 GWd/MTU

Results for Models Without Blankets

Results are presented in this section for all 624 normalized axial burnup profiles from the core follow data at assembly average burnup values of 30, 40, and 50 GWd/MTU. Cask k_{eff} values were determined for all three assembly average burnup values for each of the 624 profiles, regardless of the EOC burnup of the assembly from which the profile was taken. These models included the modeling simplification of full-length enriched fuel and were performed for both the AO and AFP isotope sets. A uniform axial burnup profile, which was depleted with the same depletion conditions and axial moderator distribution as the nonuniform profiles, is included for comparison.

Cask k_{eff} Results

The analysis of the reactivity effects of axial burnup profiles starts with a presentation of the cask k_{eff} values. These data are presented here and analysed further in the next two subsections. Table 2 shows the minimum, average, and maximum k_{eff} values for each burnup for the AO and AFP isotope sets, as well as the standard deviation of the k_{eff} values for each distribution. The values presented in the table show that a wide range of cask k_{eff} values resulted from the 624 normalized axial burnup profiles analyzed at each of the three considered burnups, and that the range increased with burnup. For the AO isotope set, the range was about 3.3% Δk at 30 GWD/MTU and increased to almost 5%

Δk at 50 GWd/MTU. For the AFP isotope set, the range was 4% Δk at 30 GWd/MTU and increased to 6.1% Δk at 50 GWd/MTU. The range of cask k_{eff} values was relatively constant in terms of standard deviations, with all six distributions (two isotope sets at each of three burnups) having a width between 3.35 and 3.77 standard deviations.

Table 2 Cask k_{eff} distribution data for unblanketed fuel models

Burnup (GWd/MTU)	AO isotope set			AFP isotope set		
	30	40	50	30	40	50
Minimum	0.85722	0.82286	0.79255	0.81010	0.77259	0.73988
Maximum	0.89052	0.86527	0.84241	0.85027	0.82220	0.80089
Average	0.87505	0.84535	0.81854	0.83154	0.79842	0.76911
Standard deviation (Δk)	0.00883	0.01201	0.01477	0.01132	0.01481	0.01763

The ten most reactive profiles were identified for the AO isotope set for each of the three burnup values considered. For the 50 GWd/MTU burnup values, the ten most reactive profiles that resulted from assemblies with 6-in. blankets were also identified. None of the profiles with 12-in. axial blankets was in the ten most reactive profiles at 30 or 40 GWd/MTU. Aside from the 12-in. blanket (hockey stick) profiles appearing in the list, the top few profiles were generally consistent among the three burnups considered. Several of the profiles resulted in cask k_{eff} values that were statistically equivalent, but the range from the most reactive to the tenth most reactive profile was large enough that there was high confidence that the most reactive profile was captured in the list presented.

The ten most reactive profiles were also identified for the AFP isotope set for each of the three burnup values considered. For the 40 and 50 GWd/MTU burnup values, the ten most reactive profiles that resulted from assemblies with 6-in. blankets were also identified. None of the profiles from assemblies with 12-in. blankets was in the ten most reactive profiles at 30 GWd/MTU. The 50 GWd/MTU burnup point was dominated by 12-in. blanket profiles; the 29 most reactive profiles resulted from these hockey stick profiles. These profiles became limiting at high burnup as the relative reactivity difference between the low-burnup top end of the assembly and the high-burnup middle portion of the assembly became greater. The low relative burnup in the top nodes caused the reactivity of that portion of the assembly to drop more slowly with burnup, and this difference increased with burnup. The limiting 6-in. blanket profiles were fairly consistent at each burnup, as with the AO isotope set. Several profiles yielded statistically equivalent cask k_{eff} values, which were also consistent with the AO isotope set results. The limiting profiles were largely the same, although in a slightly different order, for the AFP and AO isotope sets.

End effect

The difference between cask k_{eff} calculated using a distributed burnup profile and using a uniform profile is called the *end effect*. When the end effect is positive, modeling of the distributed burnup profile is more conservative. The end effect was calculated for each profile. The end effect values for the AO isotope set increased with burnup as expected, although note that all 624 profiles had a positive end effect by 30 GWd/MTU. This result was influenced by the modeling simplification made by using fully enriched fuel in place of natural blankets. At 30 GWd/MTU, the end effect varied from 0.3% Δk to 3.6% Δk; at 50 GWd/MTU, the minimum end effect increased to 3.7% Δk, and the maximum value was 8.6% Δk. The end effect values for the AFP isotope set also increased with burnup, as expected. As with the AO isotope set, all profiles resulted in positive end effects by 30 GWd/MTU. The magnitude of the end effects was significantly greater for the AFP set than for the AO set. The end effect ranged from 1.6% Δk to 5.7% Δk at 30 GWd/MTU and from 6.6% Δk to 12.7% Δk at 50 GWd/MTU. These numbers are larger than the results presented in Wagner, DeHart, and Parks [6], but the burnup profiles considered in that work were exclusively unblanketed fuel. The axial blankets in the BWR fuel assemblies reduce burnup at the ends of the assembly, increasing the severity of the burnup profile slope near the top and bottom ends of the fuel. The presence of high void fraction moderator at the top of the BWR core also leads to more severe axial burnup profile gradients than those resulting from PWR operations. These results indicate that positive end effects are possible below 20 GWd/MTU. Such positive end effects could impact peak reactivity analyses and should be studied further.

Effect of Assembly Burnup

In this study, the normalized axial burnup profiles for all 624 assemblies from a single cycle of operation were generated and analyzed, assuming depletion to three fixed burnups of 30, 40, and 50 GWd/MTU. As documented in Wagner, DeHart, and Parks [6], burnup profiles in different burnup ranges may have different characteristics. It has been demonstrated for PWR fuel that burnup profiles tend to flatten as burnup increases, allowing the use of profiles taken from lower discharged burnups at higher burnups [6]. To examine the application of this conclusion to BWR fuel, a cursory examination of the reactivity resulting from profiles taken from assemblies in different burnup ranges is warranted. Figure 2 shows the cask k_{eff} values resulting from the 568 profiles with 6-in. blankets at 50 GWd/MTU for the AO isotope set. Results for the AFP isotope set were similar, so the AFP results are not shown here. The horizontal axis of Figure 2 shows the EOC burnup of the assembly from which the profile was taken. Three burnup bins were chosen as EOC assembly average burnup of (1) <25 GWd/MTU, (2) between 25 and 40 GWd/MTU, and (3) >40 GWd/MTU. All single cycle assemblies had EOC burnups less than 25 GWd/MTU, but the selection of 40 GWd/MTU to separate the other two burnup bins is somewhat arbitrary. A line added to the figure showing the highest k_{eff} value within each bin demonstrates that cask k_{eff} values decreased by 0.5% – 1% Δk from one axial profile burnup bin to the next higher bin. This is another aspect of burnup profile selection typical of PWR BUC that may also be advantageous in extended BWR BUC; excess margin may be removed from the analysis at high burnup by considering only normalized profiles from similarly high-burnup assemblies.

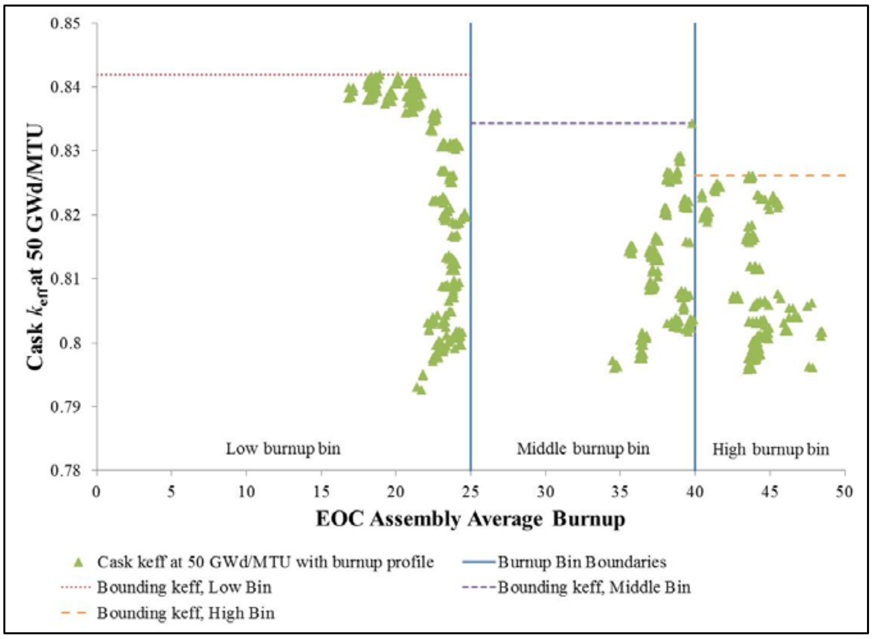

Figure 2 Cask k_{eff} value versus burnup of assembly generating profile, AO isotope set, no blankets modeled

Results for Models With Blankets

This section presents results similar to those provided in the previous section; but in this section, 6-in. natural blankets were modeled for all 624 profiles. A set of 10 of the 56 profiles with 12-in. blankets was also modeled realistically; that is, the 12-in. blanket length was modeled with natural-enrichment fuel initially. The effect of modeling the blankets was examined with respect to the cask k_{eff} values, the end effect values, and the impact of the EOC assembly burnup that generated the profile on cask k_{eff}.

Cask k_{eff} Results

Table 3 shows the minimum, average, and maximum k_{eff} values for each burnup for the AO and AFP isotope sets, as well as the standard deviation of the k_{eff} values for each distribution. The values presented in the table show that a wide range of cask k_{eff} values resulted from the 624 axial burnup profiles analyzed and that the range increased with burnup. For the AO isotope set, the range was 3.8% Δk at 30 GWD/MTU and increased to 6.4% Δk at 50 GWd/MTU. For the AFP isotope set, the range was 4.9% Δk at 30 GWd/MTU and 7.6% Δk at 50 GWd/MTU. The range of cask k_{eff} values was relatively consistent in terms of standard deviations, with all six distributions (two isotope sets at each of three burnups) having widths between 3.6 and 4.1 standard deviations. These ranges were slightly larger than for the unblanketed fuel models and tended to be wider (in terms of standard deviations) at lower burnup values. Including the natural blankets in the assembly models significantly reduced the reactivity of the hockey stick profiles.

Table 3 Cask k_{eff} distribution data for blanketed fuel models

Burnup (GWd/MTU)	AO isotope set			AFP isotope set		
	30	40	50	30	40	50
Minimum	0.83747	0.78955	0.74592	0.77978	0.72556	0.67667
Maximum	0.87507	0.84162	0.80970	0.82842	0.78949	0.75287
Average	0.85778	0.81773	0.78011	0.80618	0.75993	0.71728
Standard deviation (Δk)	0.00908	0.01306	0.01677	0.01216	0.01682	0.02104

<u>End effect</u>

The uniform burnup profile used as the reference in this section also modeled 6-in. natural-enrichment blankets to be consistent with the distributed burnup profile assembly model. The end effect values for the AO isotope set increased with burnup, as expected. Not all profiles generated positive end effects when the blankets were modeled, as opposed to the results presented in the previous section when the blankets were neglected. As the end effect increased with burnup, fewer profiles generated a negative end effect. At 30 GWd/MTU, the end effect varied from −1.6% Δ*k* to 2.2% Δ*k*; at 50 GWd/MTU, the minimum end effect increased to −1.0% Δ*k* and the maximum value was 5.4% Δ*k*. The end effect values for the AFP isotopes set also increased with burnup, as expected. Some profiles resulted in negative end effects at 30 and 40 GWd/MTU, as with the AO isotope set. At 50 GWd/MTU, all profiles resulted in positive end effects. The magnitude of the end effects was significantly greater for the AFP set than for the AO set. The end effect ranged from −1.3% Δ*k* to 3.6% Δ*k* at 30 GWd/MTU and from 0.4% Δ*k* to 8.0% Δ*k* at 50 GWd/MTU. These numbers are larger than the results presented in Wagner, DeHart, and Parks [6], but the assemblies considered in that work were exclusively unblanketed fuel. These results, as well as those from fuel neglecting the presence of the axial blankets, indicate that positive end effects are possible below 20 GWd/MTU. Such positive end effects could impact peak reactivity analyses and should be studied further.

<u>Effect of Assembly Burnup</u>

Figure 3 shows the cask k_{eff} values resulting from the 568 profiles with 6-in. blankets at 50 GWd/MTU for the AO isotope set; similar data for the AFP set are not presented here because they are qualitatively similar to the AO isotope set results. All the k_{eff} values presented were calculated at a discharge burnup of 50 GWd/MTU. The horizontal axis shows the EOC burnup of the assembly from which the profile was taken. Three burnup bins were chosen as the EOC assembly average burnup: (1) below 25 GWd/MTU, (2) between 25 and 40 GWd/MTU, and (3) above 40 GWd/MTU. As discussed previously, all single cycle assemblies had EOC burnups less than 25 GWd/MTU, but the selection of 40 GWd/MTU to separate the other two burnup bins is somewhat arbitrary. A line added to each figure, showing the highest k_{eff} value within each bin, demonstrates that cask k_{eff} values decreased by about 1% Δk from one axial profile burnup bin to the next higher bin. This is another aspect of burnup profile selection typical of PWR BUC that may also be advantageous in extended BWR BUC.

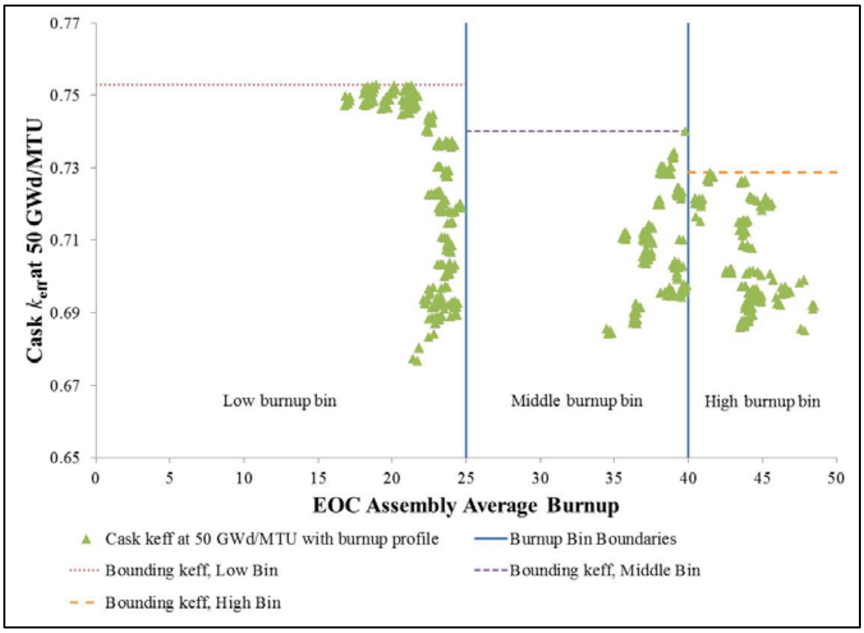

Figure 3 Cask k_{eff} value versus burnup of assembly generating profile, AO isotope set, blankets modeled

Conclusions

This paper documents studies performed to examine the effect of axial burnup distributions on extended BWR BUC. The burnup range examined was 30–50 GWd/MTU. The lower burnup was selected to be higher than the burnups typical of peak reactivity for fuel lattices, whereas the upper bound was typical of discharge burnups for BWR assemblies. Detailed calculations were performed using 624 axial burnup profiles generated from a proprietary core follow data.

The following recommendations can be made based on the results of this study:

- The choice of axial burnup profiles can have significant impacts on cask reactivity. The range of cask k_{eff} values resulting from the profiles used in this study was as large as 7.6% Δk. Applicants must provide justification for the profiles used in an analysis, including the burnups over which uniform and distributed burnup profiles are used. Some guidance on axial burnup profile selection is provided in Marshall, Ade, Bowman, and Martinez-Gonzalez [7].

- The limiting profile resulting from a set of available profiles is largely independent of the isotope set used. Axial blanket modeling approaches also have only a small impact on identifying the limiting profile for assemblies with 6-in. natural blankets.
- Distributed burnup profiles must be considered for extended BWR BUC. End effects of up to 12.7% Δk were identified in this study. These results indicate that positive end effects are possible below 20 GWd/MTU. Such positive end effects could impact peak reactivity analyses and should be studied further.
- Axial feature differences in the top 4 ft of the assembly, such as differences in blanket lengths, are likely to require separate consideration. Any scheme used to identify potentially limiting axial burnup profiles should be justified.
- Grouping axial burnup profiles into bins based on the EOC burnup of the assembly from which the profile was taken is likely to lower calculated cask k_{eff} values at higher burnups.

Acknowledgments

Funding for this work was provided by the U.S. Nuclear Regulatory Commission (NRC). The authors would like to thank Mourad Aissa and other staff members of the NRC Office of Nuclear Regulatory Research for their helpful comments and support. Special thanks to Ben Betzler, Justin Clarity, and Mike Dunn from ORNL for their reviews and insightful comments, and to Kristin Gunter Ellestad for assistance with the preparation of this document.

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