Impact of Integral Burnable Absorbers on PWR Burnup Credit Criticality Safety Analyses

Charlotta E. Sanders and John C. Wagner

Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6370

sandersc@ornl.gov wagnerjc@ornl.gov
(865) 574-5279 (865) 241-3570

Executive Summary

The utilization of credit for fuel burnup necessitates consideration of a wide range of fuel designs and operating conditions, including the use of integral burnable absorbers (IBAs). The Interim Staff Guidance on burnup credit (ISG-8) issued by the Nuclear Regulatory Commission's Spent Fuel Project Office recommends licensees restrict the use of burnup credit to assemblies that have not used burnable absorbers. This restriction eliminates a large portion of the currently discharged spent fuel assemblies from cask loading, and thus severely limits the practical usefulness of burnup credit. This paper examines the effect of IBAs on reactivity to provide technical justification for relaxing the current restriction for dry cask storage and transport, and subsequently, to develop the necessary guidelines for relaxing the current restriction.

Analyses have been performed for Westinghouse assembly designs with Integral Fuel Burnable Absorber (IFBA) rods, Combustion Engineering (CE) and Siemens assembly designs with UO_2-Gd_2O_3 rods, and CE assembly designs with UO_2-Er_2O_3 and Al_2O_3-B_4C rods. Analyses are presented for a realistic range of initial fuel enrichment and poison loading combinations based on plant data. The effects are quantified, and trends with initial fuel enrichment and poison loading are noted. The results demonstrate that assembly designs with IBAs other than IFBA rods are less reactive throughout burnup than their corresponding designs without the IBA rods (i.e., nonpoisoned, equivalent enrichment). Consequently, with the exception of assemblies with IFBA rods, neglecting the presence of IBAs in a burnup-credit criticality safety evaluation will yield slightly conservative results. Note, however, that three-dimensional cask calculations have demonstrated (for a single representative case) that when the axial burnup distribution is included, assemblies with IFBA rods are also less reactive (than corresponding assemblies without IFBA rods) due to the residual absorber in the low-burnup end regions. Additional cases are being analyzed to solidify this conclusion.

1. Introduction

The concept of taking credit for the reduction in reactivity of burned or spent nuclear fuel (SNF) due to fuel burnup is commonly referred to as *burnup credit*. The reduction in reactivity that occurs with fuel burnup is due to the net reduction of fissile nuclide concentrations and the production of actinide and fission-product neutron absorbers. The change in the inventory of

these nuclides with fuel burnup, and the consequent reduction in reactivity, is dependent upon the depletion environment. Therefore, the use of burnup credit necessitates consideration of all possible fuel operating conditions, including the use of integral burnable absorbers (IBAs).
The Interim Staff Guidance on burnup credit [1] issued by the Nuclear Regulatory Commission's (NRC) Spent Fuel Project Office recommends licensees restrict the use of burnup credit to assemblies that have not used burnable absorbers (e.g., IBAs or burnable poison rods, BPRs). This restriction eliminates a large portion of the currently discharged spent fuel assemblies from cask loading, and thus severely limits the practical usefulness of burnup credit. The reason for this restriction is that the presence of burnable absorbers during depletion hardens the neutron spectrum, resulting in lower ^{235}U depletion and higher production of fissile plutonium isotopes. Enhanced plutonium production has the effect of increasing the reactivity of the fuel at discharge and beyond. Consequently, an assembly exposed to burnable absorbers may have a slightly higher reactivity for a given burnup than an assembly that has not been exposed to burnable absorbers. This paper examines the effect of IBAs on reactivity for various designs and enrichment/poison loading combinations as a function of burnup. The effect of BPRs, which are typically removed during operation, is addressed elsewhere [2].

2. Background

All of the commonly used fuel assembly designs featuring IBAs are similar in that they contain thermal neutron absorbing material as an integral non-removal part of the assembly. However, there are design differences in IBA material, composition, placement within rods, and rod configurations, along with variations in fuel enrichment. The IBA types that have been widely used in U.S. pressurized-water reactors (PWRs) include Westinghouse assembly designs with Integral Fuel Burnable Absorber (IFBA) rods, Combustion Engineering (CE) and Siemens assembly design with UO_2-Gd_2O_3 rods, CE assembly designs with UO_2-Er_2O_3 rods, and CE assembly designs with Al_2O_3-B_4C rods. For PWR fuels without IBAs, reactivity decreases with burnup in a nearly linear fashion. In contrast, for PWR fuel assembly designs that make significant use of IBAs, reactivity actually increases as fuel burnup proceeds, reaches a maximum at a burnup where the IBA is nearly depleted, and then decreases with burnup in a nearly linear fashion. For fuel assembly designs that make modest use of IBAs, reactivity remains relatively constant or slowly decreases with burnup (up to the point where the IBA is nearly depleted), and then decreases with burnup in the nearly linear manner. The assemblies are typically designed such that the burnable absorber is effectively depleted in the first third of the assembly life, and as a result, the assembly reactivity typically peaks within this period of burnup.

Although a great deal of work has been performed related to IBA designs and development for greater fuel utilization and reactor core performance, studies to assess the significance of IBAs on the reactivity of discharged fuel are minimal. Recent work [3] has provided illustrative examples intended to represent typical magnitudes of the reactivity effects of a few IBA types. Although the analyses were limited to a single case for each type of IBA, the study concluded that neglecting IBAs yields conservative results for assemblies that utilize UO_2-Gd_2O_3 and UO_2-Er_2O_3 rods and non-conservative results for assemblies that utilize IFBA rods. Further, the study showed that the reactivity effect from IBAs is generally small and well behaved.

The following sections provide an overview of the calculational approach used for this study and present detailed analyses to demonstrate the reactivity effect of IBAs as a function of burnup. The analyses include variations in the IBA type, concentration, and initial fuel enrichment. All of the IBA types that have been widely used in U.S. PWRs are considered.

3. Approach

Depletion calculations were performed using the HELIOS-1.6 code package [4], which primarily consists of three programs: AURORA, HELIOS, and ZENITH. HELIOS is a two-dimensional (2-D), transport theory code based on the method of collision probabilities with current coupling. All calculations are for an infinite radial array of fuel assemblies and utilize all of the actinide and fission product nuclides included in the 45-group neutron cross-section library, based on ENDF/B-VI data, that is distributed with the HELIOS-1.6 code package. The various structures within each of the assembly models were coupled using angular current discretization (interface currents). Using the isotopic compositions from the depletion calculations, branch or restart calculations were performed to determine the neutron-multiplication factor as a function of burnup for out-of-reactor conditions (i.e., unborated moderator at 20°C) and zero cooling time. The depletion calculations were performed using a fuel temperature of 1000 K, moderator temperature of 600 K, and soluble boron concentration of 650 ppm as well as specific power of 60 MW/MTU.

In general, for each unique IBA assembly design considered, a calculation was performed for (1) the actual assembly specification (i.e., with IBAs present) and (2) an unpoisoned condition in which the IBA rods were replaced by equivalent enrichment UO_2 fuel rods. Throughout the paper, the Δk values between these two conditions are reported to assess the effect of IBAs on the reactivity of SNF.

In addition, analyses in support of burnup credit featuring the effects of cask geometry (presence of fixed absorbers), cooling time, and axial burnup distribution are also presented and discussed at the end of the following section. These analyses were performed to confirm the applicability of the infinite assembly array calculations. Also, the KENO V.a Monte Carlo code [5] was employed for the calculations describing the effect of axial burnup distribution.

4. Results and Discussion

The following subsections present a summary of the analyses [6] that have been performed to establish and quantify the effect of IBAs on the reactivity of SNF. The interested reader is referred to Ref. [6] for additional comparisons and detailed absorber and fuel design specifications.

<u>Integral Fuel Burnable Absorber (IFBA) Rods</u>

The IFBA, developed by Westinghouse, consists of a thin coating of zirconium diboride (ZrB_2) on the outer surface of the fuel pellets. Various IFBA loading patterns [0 (no IFBA), 32, 64, 80, 104, 128, and 156 IFBA rods] with boron loading of 1.57 mg ^{10}B/inch, and initial fuel enrichment of 4.0 wt % ^{235}U were studied for a Westinghouse 17×17 fuel assembly design in

order to establish the reactivity effect as a function of burnup. Figure 1 displays k_{inf} values as a function of burnup and number of IFBA rods. Note that when a large number of IFBA rods are present reactivity increases with burnup until the burnable absorber is virtually depleted. On the contrary, when a small number of IFBA rods are present, reactivity decreases slowly with burnup until the burnable absorber is essentially depleted. Figure 2 displays the difference in k_{inf} values (Δk values) for cases with IFBA rods and a reference case without IFBA rods as a function of burnup. The figure demonstrates that the Δk values become positive after the point at which the boron is more or less depleted. Further, it can be seen that this positive reactivity effect increases with increasing numbers of IFBA rods. Additional studies have shown that for a fixed number of IFBA rods, the maximum positive Δk value increases slightly with decreasing fuel enrichment [6].

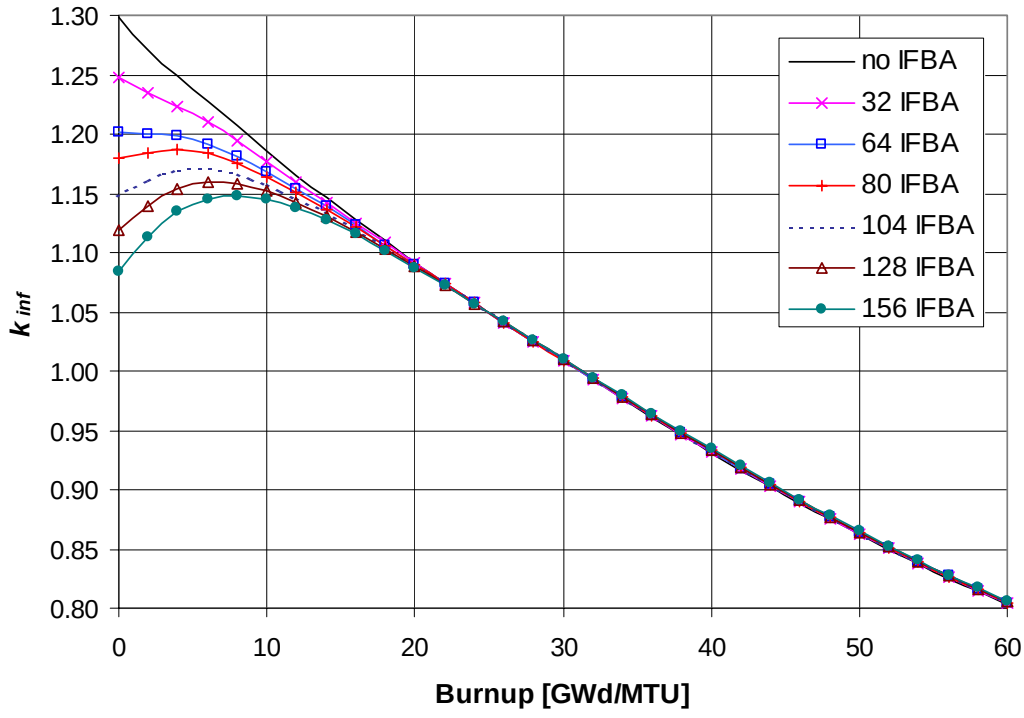

Figure 1. Trends in k_{inf} for PWR fuel as a function of IFBA loading.

Analyses were performed for variations in the initial fuel enrichment, the numbers of IFBA rods, and the ^{10}B loading in the IFBA rods, within their respective ranges (according to actual plant fuel data). The maximum positive Δk value was found to be 0.004, which corresponded to the maximum ^{10}B loading (2.355 mg ^{10}B/inch) and maximum number of IFBA rods (i.e., 156), for an initial enrichment of 4.617 wt % ^{235}U.

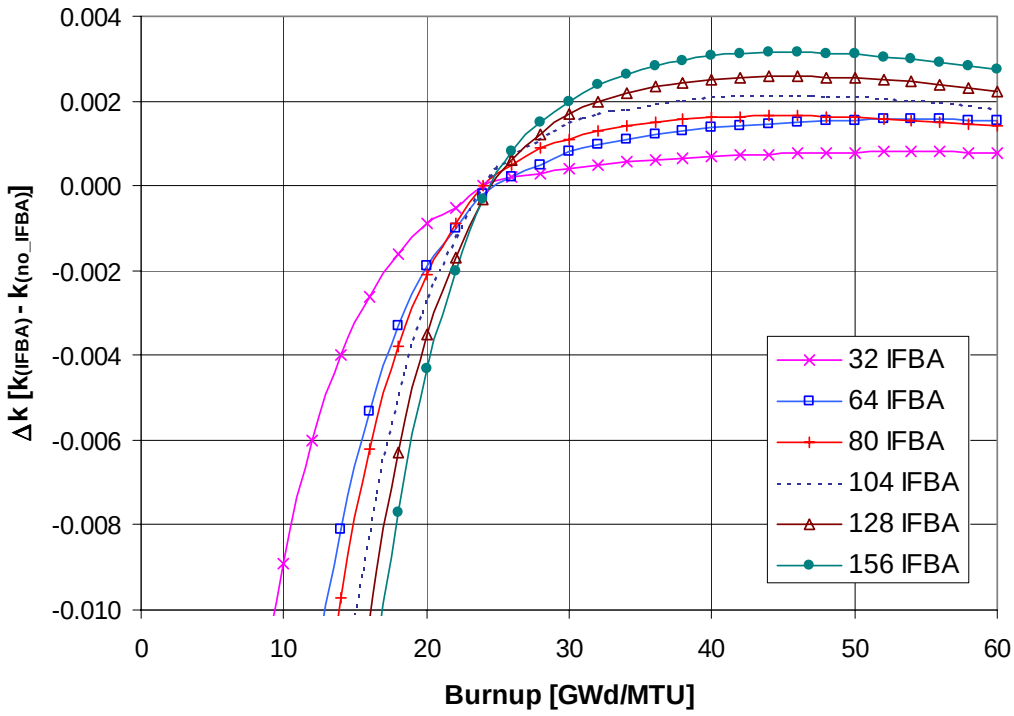

Figure 2. Comparison of Δk values, as a function of burnup, between assemblies with and without IFBA rods present.

<u>UO_2-Gd_2O_3 Rods</u>

UO_2-Gd_2O_3 rods are fuel rods with Gd_2O_3 as an integral part of the fuel matrix. The loading of Gd_2O_3 in each gadolinia-bearing rod and the number of gadolinia rods within an assembly are both variable. The Siemens 17×17 assembly designs considered for the analysis of these gadolinia rods, designated S1–S4, feature various gadolinia and enrichment combinations, which are summarized in Table 1. Unpoisoned, equivalent enrichment reference cases (corresponding to S1–S4) were also analyzed and used for comparison. The Δk as a function of burnup for the assemblies is shown in Figure 3, where it can be seen that all of the gadolinia-bearing fuel assembly designs yield a negative Δk. These results indicate that the gadolinia-bearing fuel k_{inf} is less than the non-gadolinia-bearing fuel k_{inf} and the difference between the two cases increases with increasing gadolinia loading (wt % Gd_2O_3 and the number of gadolinia-bearing rods).

In general, the use of gadolinia has some known inherent penalties [7], e.g., a residual negative reactivity remains following the depletion of ^{155}Gd and ^{157}Gd. As mentioned earlier, gadolinia is an integral part of the fuel matrix, which means that the gadolinia displaces uranium resulting in a reduced heavy metal mass. A study [6] was carried out to investigate the magnitude of the residual effect in gadolinia as well as to see if there are residual effects of the boron poison (used in IFBA rods). It was determined that there are no significant residual effects for IFBAs, which explains why Δk is positive for fuel assembly designs containing IFBA rods but is negative for gadolinia-bearing fuel assembly designs.

Table 1. Specifications for Siemens 17 × 17 fuel assemblies with UO_2-Gd_2O_3 fuel rods

Fuel assembly designator	*UO_2 fuel rod enrichment*	*No. of UO_2 fuel rods*	*No. of UO_2-Gd_2O_3 rods*	*Gd_2O_3 / ^{235}U wt % for UO_2-Gd_2O_3 rods*
S1	4.25	260	4	2.00 / 4.16 [a]
S2	4.25	244	16 4	6.00 / 3.99 2.00 / 4.16
S3	4.25	240	16 8	8.00 / 3.91 4.00 / 4.08
S4	4.25	236	16 12	8.00 / 3.91 4.00 / 4.08

[a] Read as 2.0 wt % Gd_2O_3 and 4.16 wt % ^{235}U in UO_2-Gd_2O_3 rods.

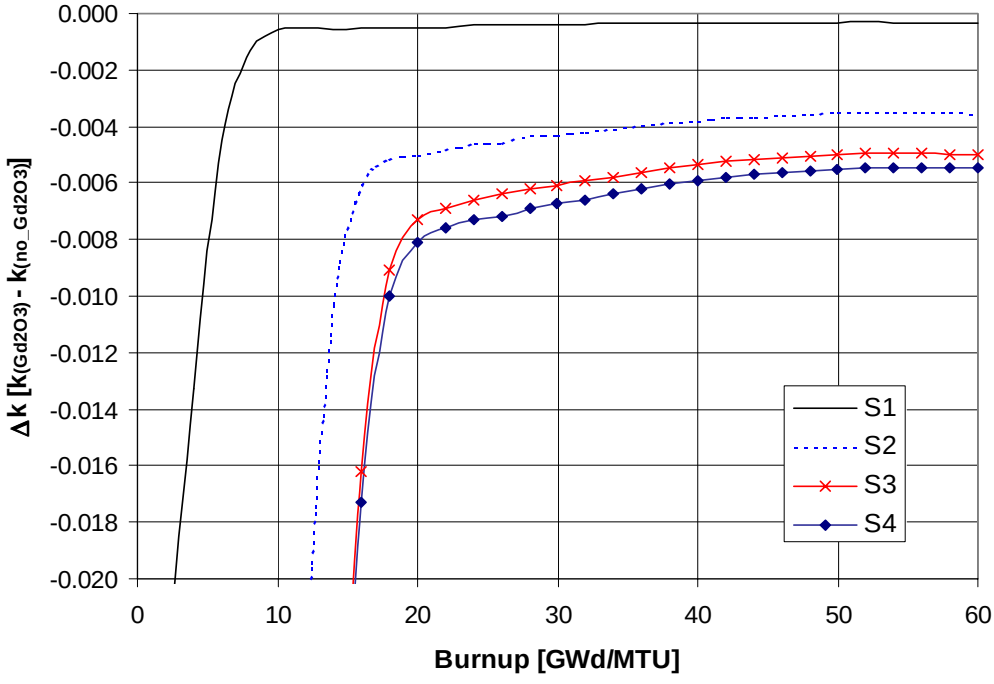

Figure 3. Comparison of Δk values, as a function of burnup, between assemblies with and without UO_2-Gd_2O_3 rods present.

UO_2-Er_2O_3 Rods

Considered for this study is the CE manufactured IBA rod containing erbia (Er_2O_3) used in the 14×14 fuel assembly design. Similar to the UO_2-Gd_2O_3 rods, the erbia-bearing rods include the burnable absorber (Er_2O_3) as an integral part of the fuel matrix. As a result, the use of erbia rods has similar inherent residual penalties to those identified for gadolinia rods. The weight percent of the erbia and the number of erbia-bearing rods within an assembly are both variable, as well as the ^{235}U enrichment. Figure 4 shows k_{inf} values as a function of burnup and number of erbia-bearing rods. The fuel enrichment is 4.3 wt % ^{235}U and the weight percent of Er_2O_3 is 2.0. A plot of Δk as a function of burnup for the assemblies is shown in Figure 5, where it can be seen that the erbia-bearing fuel assembly designs yield a negative Δk. Further, the extent by which the erbia-bearing fuel is less reactive increases with increasing erbia loading.

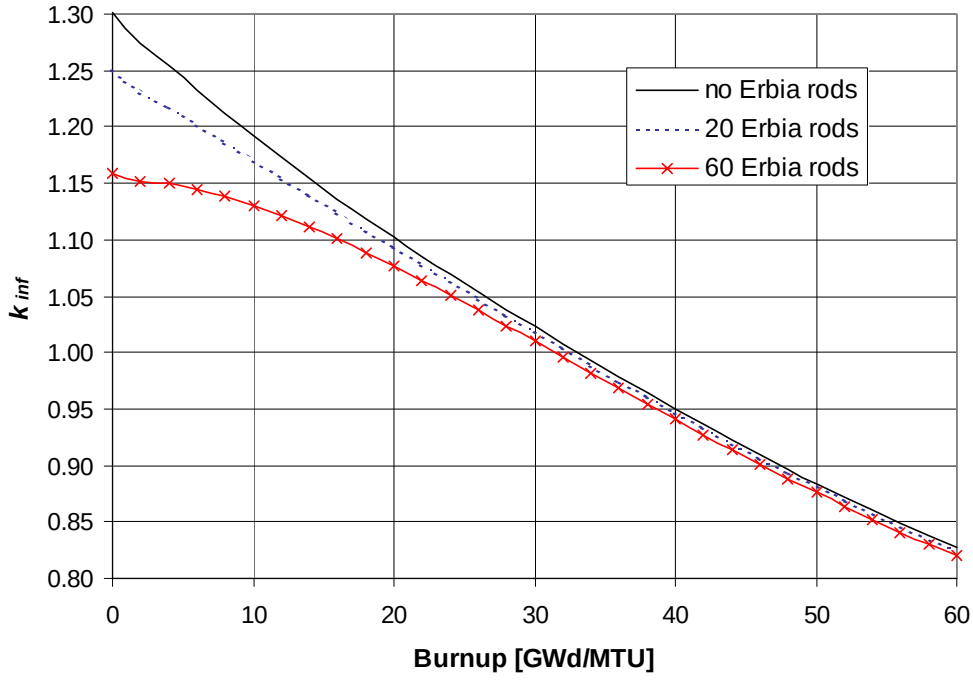

Figure 4. Reactivity behavior of PWR fuel with and without UO_2-Er_2O_3 (2.0 wt % Er_2O_3) rods present.

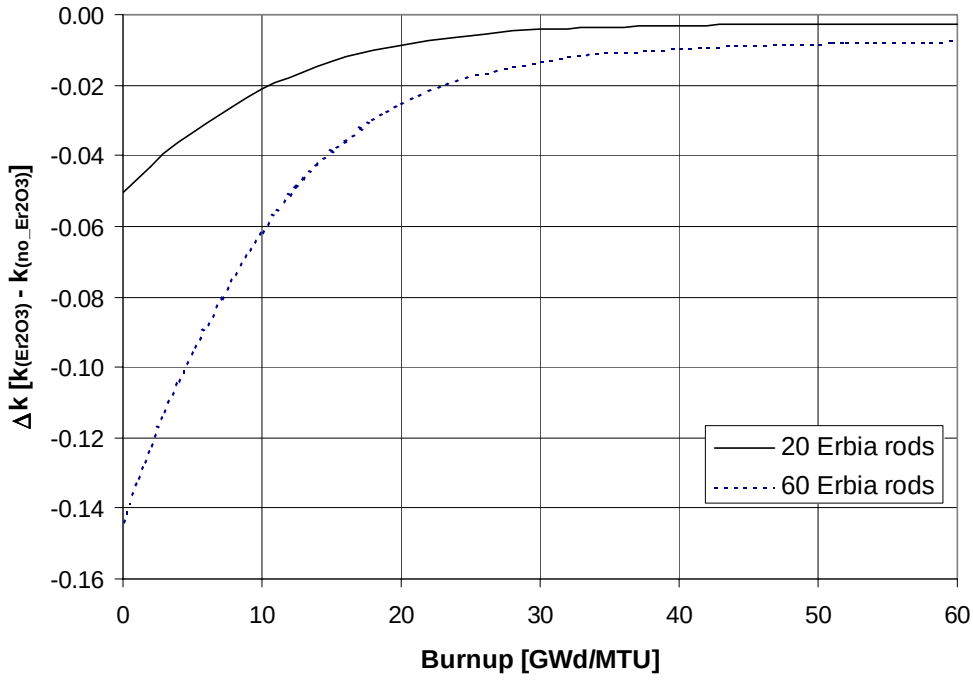

Figure 5. Comparison of Δk values as a function of burnup between assemblies with and without Er_2O_3 fuel rods present.

<u>Al_2O_3-B_4C Rods</u>

Another IBA manufactured by CE consists of solid rods containing aluminum pellets with uniformly dispersed boron carbide particles (Al_2O_3-B_4C), clad in zircaloy. Unlike the IFBA, UO_2-Gd_2O_3, and UO_2-Er_2O_3, these rods do not contain fuel and are referred to as burnable poison rods elsewhere [8]. However, because the Al_2O_3-B_4C rods are an *integral*, nonremovable part of the fuel assembly they are classified in this work as IBAs. The weight percent of B_4C and the number of rods per assembly are variable. Based on the available specifications, calculations were performed for CE 14×14 assemblies with 4.0 wt % ^{235}U initial enrichment and various numbers of Al_2O_3-B_4C rods (4.0 wt % B_4C). Figure 6 shows the k_{inf} values as a function of burnup for the CE assemblies with various numbers of Al_2O_3-B_4C rods present. For the case without Al_2O_3-B_4C rods, the Al_2O_3-B_4C rods were replaced by nominal UO_2 (4.0 wt % ^{235}U) fuel rods. Differences in the k_{inf} values (Δk values) between cases with and without the Al_2O_3-B_4C rods present are shown in Figure 7, which confirms expectations that replacing fuel rods with Al_2O_3-B_4C rods results in a reduction in assembly reactivity at discharge.

.

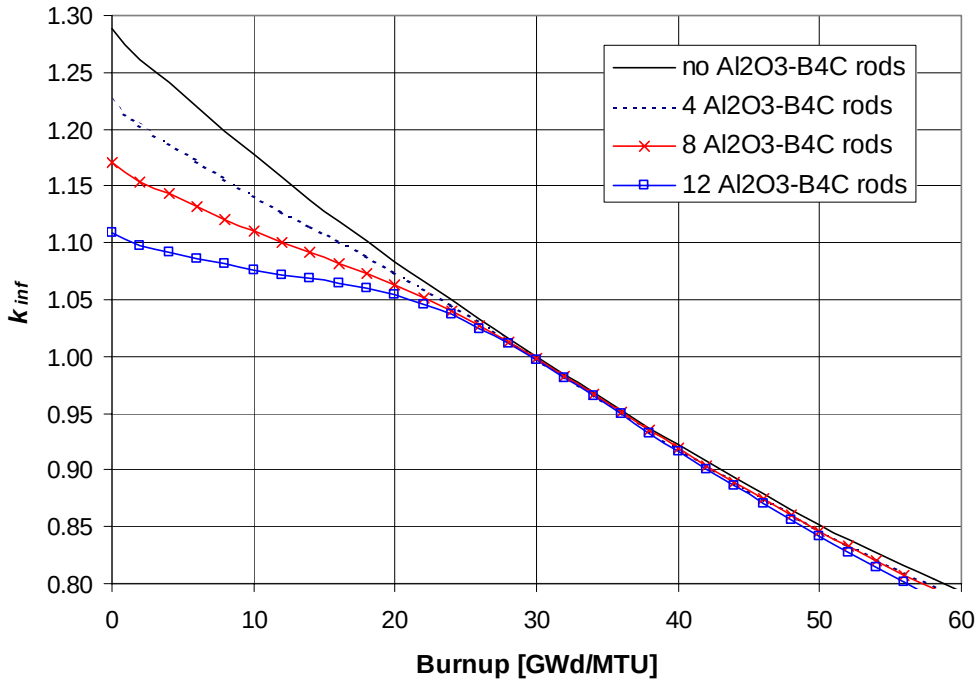

Figure 6. Reactivity behavior of PWR fuel with and without Al_2O_3-B_4C (4.0 wt % B_4C) rods present.

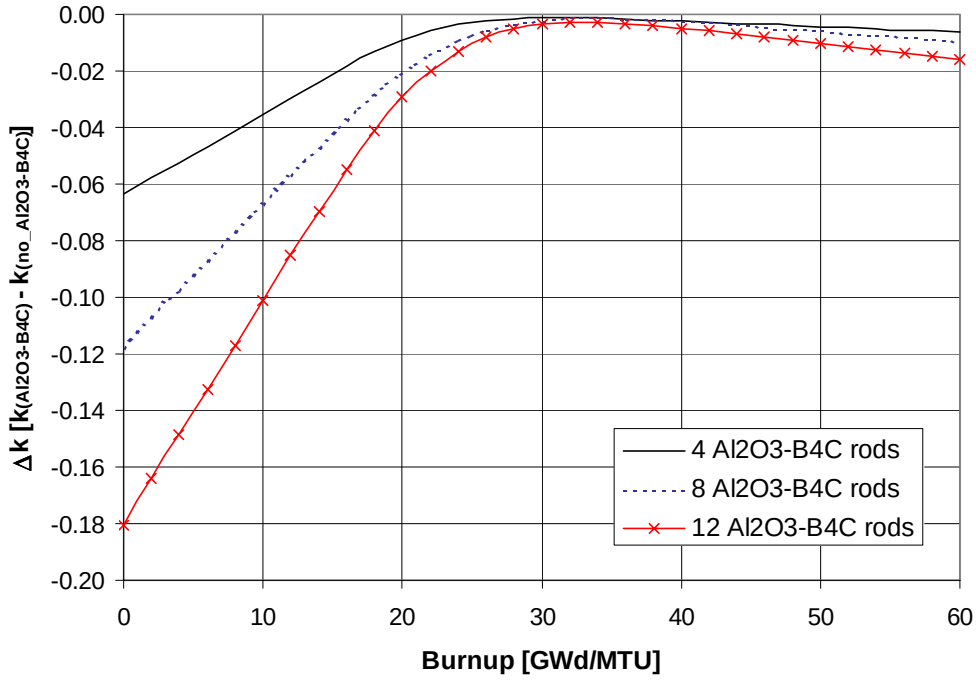

Figure 7. Comparison of Δk values as a function of burnup between assemblies with and without Al_2O_3-B_4C rods present.

Additional Studies

As this study was performed in support of burnup credit, a number of the calculations discussed above were repeated with modeling assumptions and conditions associated with burnup credit analyses to assess their impact on the results. In particular, the effect of cask geometry, cooling time, and axial burnup distribution were studied for selected cases.

In order to evaluate the impact of fixed absorbers (e.g., Boral panels), since they are commonly used in SNF storage cells and affect the neutron spectrum, a number of 2-D HELIOS calculations were repeated for a cask storage cell array geometry [9]. While the presence of fixed absorbers generally tends to increase k_{inf} values with respect to cases without fixed absorbers, the study demonstrated that as the IBA material is depleted, the differences become very small with burnup. Calculations were also performed to evaluate the effect of cooling times representative of cask storage and transportation (i.e., 5-40 years). The results showed that the Δk values between cases with and without IBAs were insensitive to cooling time.

Inclusion of an axial burnup distribution can result in an increase in the neutron multiplication factor for SNF, as compared to the uniform axial burnup modeling assumption, and thus is an important part of a burnup credit analysis. The increase in reactivity is due to the under-burned (with respect to the assembly-average burnup) regions near the fuel ends. With IBAs in a fuel assembly, the under-burned end regions will have more residual absorber material present than the center region. Therefore, it was anticipated that the positive reactivity effect of the axial burnup distribution would actually be suppressed by the presence of IBAs. To evaluate this expectation, 3-D criticality calculations were performed with the GBC-32 cask [9] using the KENO V.a Monte Carlo code and spent-fuel isotopics from HELIOS depletion calculations. Because the IFBA rods were the only IBA type to yield a positive reactivity effect, they were used for this study.

A comparison was made between cases with no IFBA rods present and cases with 104 IFBA rods present, with a poison loading of 1.57 mg ^{10}B/inch. The fuel in both cases had an initial enrichment of 4.0 wt % ^{235}U and assembly-average burnups of 15, 30, 45, and 60 GWd/MTU were considered. As expected, for a typical initial enrichment and discharge burnup combination (i.e., 4.0 wt % ^{235}U and 45 GWd/MTU), the case with IFBA rods yielded a slightly lower (~0.005 Δk) effective neutron multiplication factor, k_{eff}, than the case without IFBA rods present (both cases include the axial burnup distribution). This is due to the small residual IBA material in the under-burned end regions, which dominate the neutron multiplication in the SNF. Additional comparisons for both higher and lower assembly-average burnups confirm that the difference between cases with and without IFBAs decreases with burnup; for high burnup (i.e., 60 GWd/MTU) where the residual absorber in the end regions is essentially depleted, the difference is very small.

5. Conclusions

The analyses presented above demonstrate that the neutron multiplication factor for an assembly without IBAs is always greater (as a function of burnup) than the neutron multiplication factor for an assembly that utilized any of the following IBA types: UO_2-Gd_2O_3, UO_2-Er_2O_3, or

Al_2O_3-B_4C rods. Conversely, k_{inf} values for assemblies with IFBA rods present were found to exceed those of assemblies without IFBA rods. In all cases, for burnups characteristic of discharge, the reactivity effect of IBAs is relatively small and generally well behaved. These results are important to burnup credit because they demonstrate that assembly designs with UO_2-Gd_2O_3, UO_2-Er_2O_3, or Al_2O_3-B_4C IBA rods are less reactive throughout burnup than their corresponding designs without the IBA rods (i.e., nonpoisoned, equivalent enrichment). Consequently, with the notable exception of assemblies with IFBA rods, neglecting the presence of IBAs in a burnup credit criticality safety evaluation will yield slightly conservative results. Note, however, that three-dimensional cask calculations have demonstrated (for a single representative case) that when the axial burnup distribution is included, assemblies with IFBA rods are also less reactive (than corresponding assemblies without IFBA rods) due to the residual absorber in the low-burnup end regions. Additional cases are being analyzed to solidify this conclusion.

References

1. *Spent Fuel Project Office Interim Staff Guidance – 8, Rev. 1 – Limited Burnup Credit*, U.S. Nuclear Regulatory Commission, July 30, 1999.

2. J. C. WAGNER and C. V. PARKS, *Parametric Study of the Effect of Burnable Poison Rods for PWR Burnup Credit*, ORNL/TM-2000/373, Oak Ridge National Laboratory (2001).

3. P. M. O'LEARY and M. L. PITTS, "Effects of Integral Burnable Absorbers on PWR Spent Nuclear Fuel," *Trans. Am. Nucl. Soc.* **83**, November 2000.

4. J. J. CASAL, R. J. J. STAMM'LER, E. A. VILLARINO, and A. A. FERRI, "HELIOS: Geometric Capabilities of a New Fuel-Assembly Program," Vol. 2, p. 10.2.1 113, *Intl Topical Meeting on Advances in Mathematics, Computations, and Reactor Physics*, Pittsburgh, Pennsylvania, April 28–May 2, 1991.

5. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation*, NUREG/CR-0200, Rev. 6 (ORNL/NUREG/CSD-2/R6), Vols. I, II, and III, May 2000. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-545.

6. C. E. SANDERS and J. C. WAGNER, *Study of the Effect of Integral Burnable Absorbers for PWR Burnup Credit*, ORNL/TM-2000/321, Oak Ridge National Laboratory (2001).

7. M. SCLIECK, H-D. BORGER, and A. NEUFERT, "Optimized Gadolinia Concepts for Advanced In-Core Fuel Management in PWRs," *Nucl. Eng. Design*, **205**, p. 191 (2001).

8. Calvert Cliffs Nuclear Power Plant UFSAR, Rev. 26, Constellation Nuclear.

9. J. C. WAGNER, *Computational Benchmark for Estimation of Reactivity Margin from Fission Products and Minor Actinides in PWR Burnup Credit*, ORNL/TM-2000/306, Oak Ridge National Laboratory (2001).