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

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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). On the other hand, IFBA rods were found to be more reactive at discharge burnup than assemblies without IFBA rods. Thus, neglecting the presence of IBAs other than IFBAs in a burnup-credit criticality safety evaluation will yield slightly conservative results; however, IFBAs must be accounted for in a safety evaluation.

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 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 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.

Integral Fuel Burnable Absorber (IFBA) Rods

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 demonstrate that for a given fuel enrichment, 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].
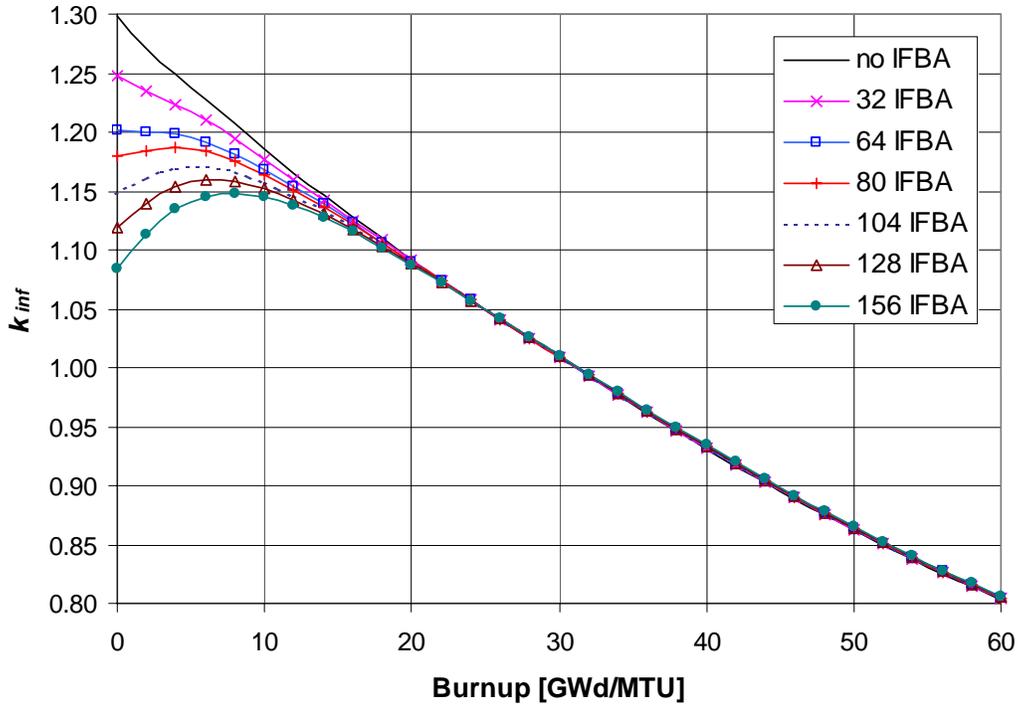
Figure 1. Trends in k_{inf} for PWR fuel as a function of IFBA loading.

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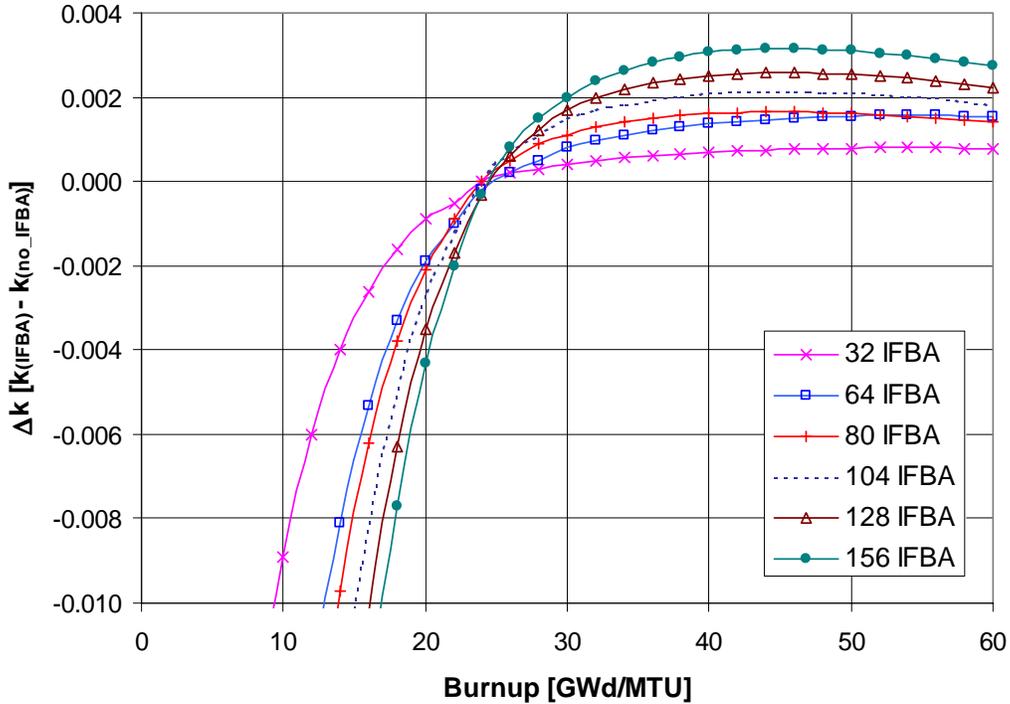
Figure 2. Comparison of Δk values, as a function of burnup, between assemblies with and without IFBA rods present.

UO$_2$-Gd$_2$O$_3$ Rods

UO$_2$-Gd$_2$O$_3$ rods are fuel rods with Gd$_2$O$_3$ as an integral part of the fuel matrix. The loading of Gd$_2$O$_3$ 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, respectively) same as UO$_2$-GdO$_2$ rod except Gd$_2$O$_3$ is removed 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$_2$O$_3$ 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

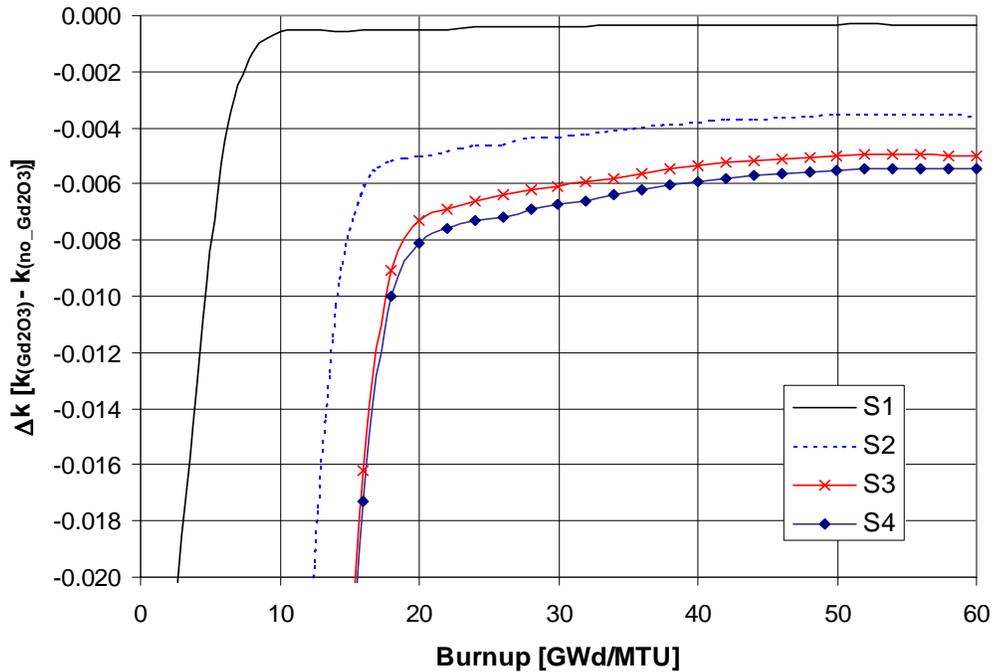[a] Read as 2.0 wt % Gd_2O_3 and 4.16 wt % ${}^{235}U$ in UO_2-Gd_2O_3 rods.

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

<u>UO$_2$-Er$_2$O$_3$ Rods</u>

Considered for this study is the CE manufactured IBA rod containing erbia (Er$_2$O$_3$) used in the 14×14 fuel assembly design. Similar to the UO$_2$-Gd$_2$O$_3$ rods, the erbia-bearing rods include the burnable absorber (Er$_2$O$_3$) 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$_2$O$_3$ 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 all of 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.
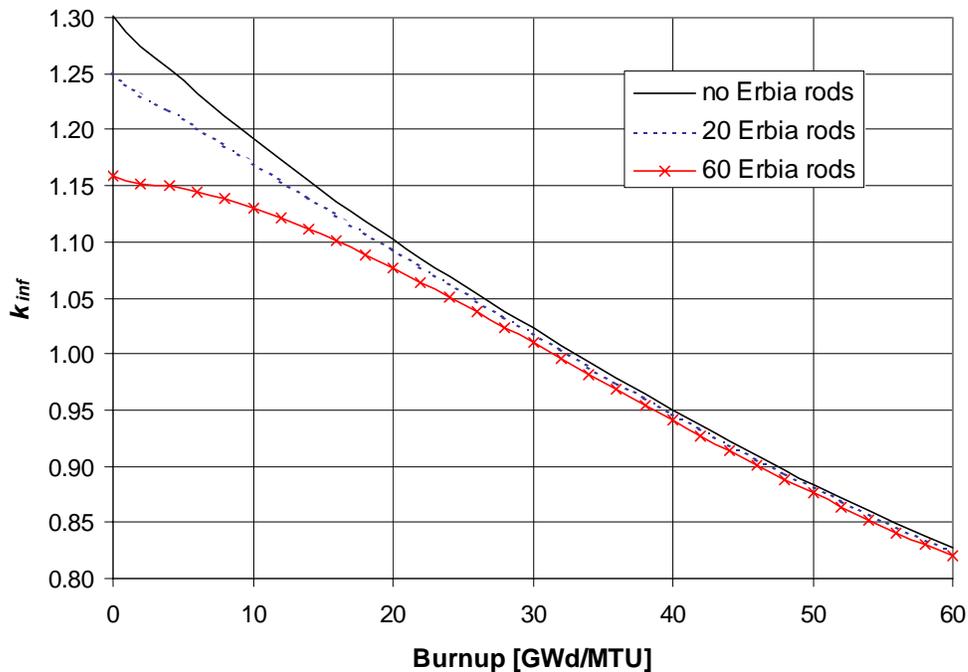

Figure 4. Reactivity behavior of PWR fuel with and without UO$_2$-Er$_2$O$_3$ (2.0 wt % Er$_2$O$_3$) rods present.

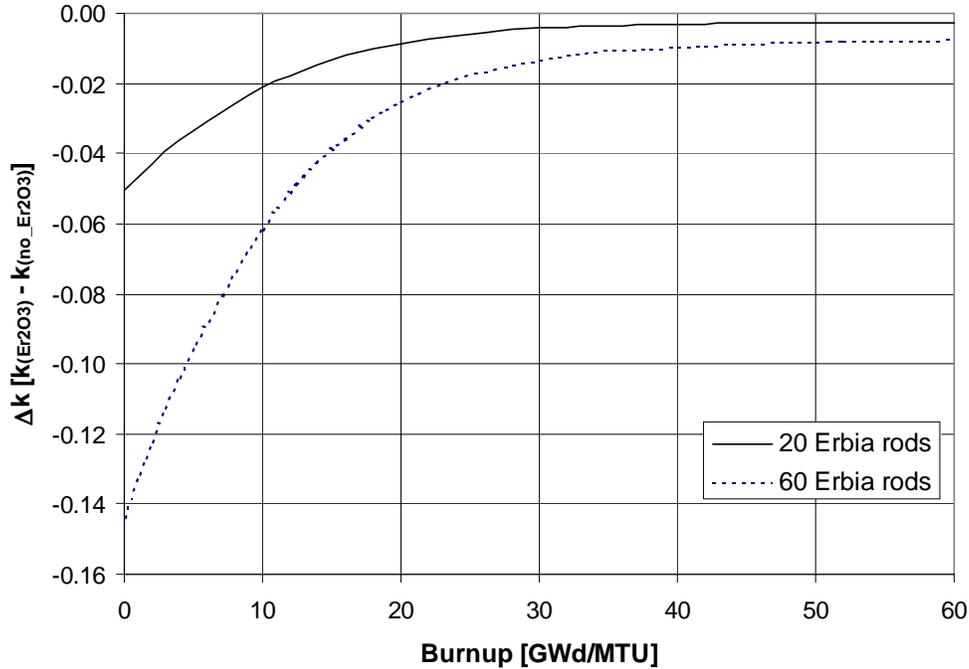Figure 5. Comparison of Δk values as a function of burnup between assemblies with and without Er_2O_3 fuel rods present.

Al$_2$O$_3$-B$_4$C Rods

Another IBA manufactured by CE consists of solid rods containing aluminum pellets with uniformly dispersed boron carbide particles (Al$_2$O$_3$-B$_4$C), clad in zircaloy. Unlike the IFBA, UO$_2$-Gd$_2$O$_3$, and UO$_2$-Er$_2$O$_3$, these rods do not contain fuel and are referred to as burnable poison rods elsewhere [8]. However, because the Al$_2$O$_3$-B$_4$C rods are an *integral*, nonremovable part of the fuel assembly they are classified in this work as IBAs. The weight percent of B$_4$C 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$_2$O$_3$-B$_4$C rods (4.0 wt % B$_4$C). Figure 6 shows the k_{inf} values as a function of burnup for the CE assemblies with various numbers of Al$_2$O$_3$-B$_4$C rods present. For the case without Al$_2$O$_3$-B$_4$C rods, the Al$_2$O$_3$-B$_4$C 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$_2$O$_3$-B$_4$C rods present are shown in Figure 7, which confirms expectations that replacing fuel rods with Al$_2$O$_3$-B$_4$C rods results in a reduction in assembly reactivity at discharge.

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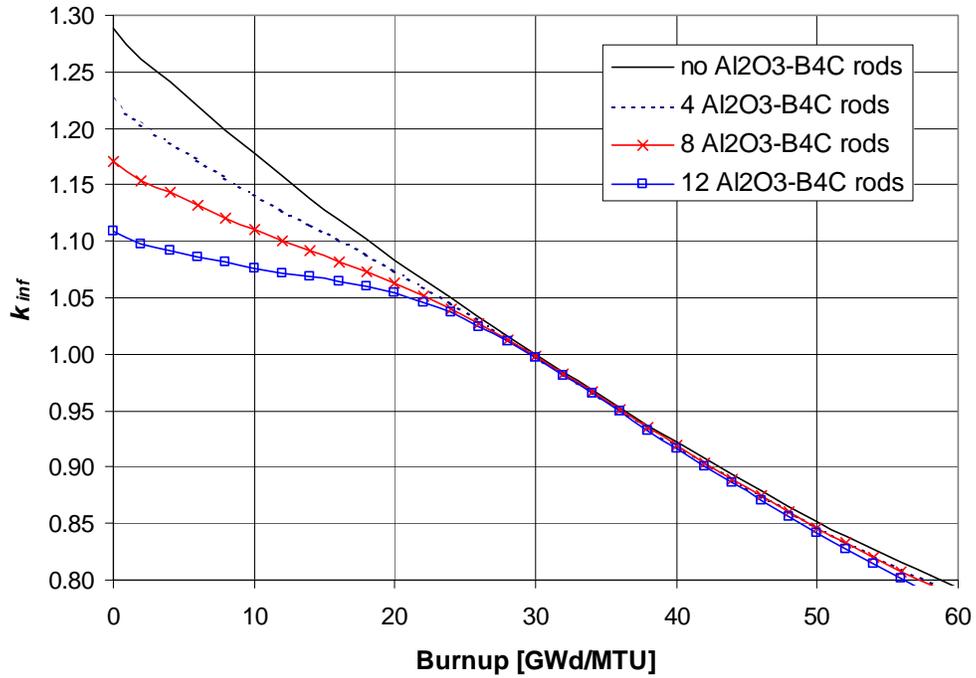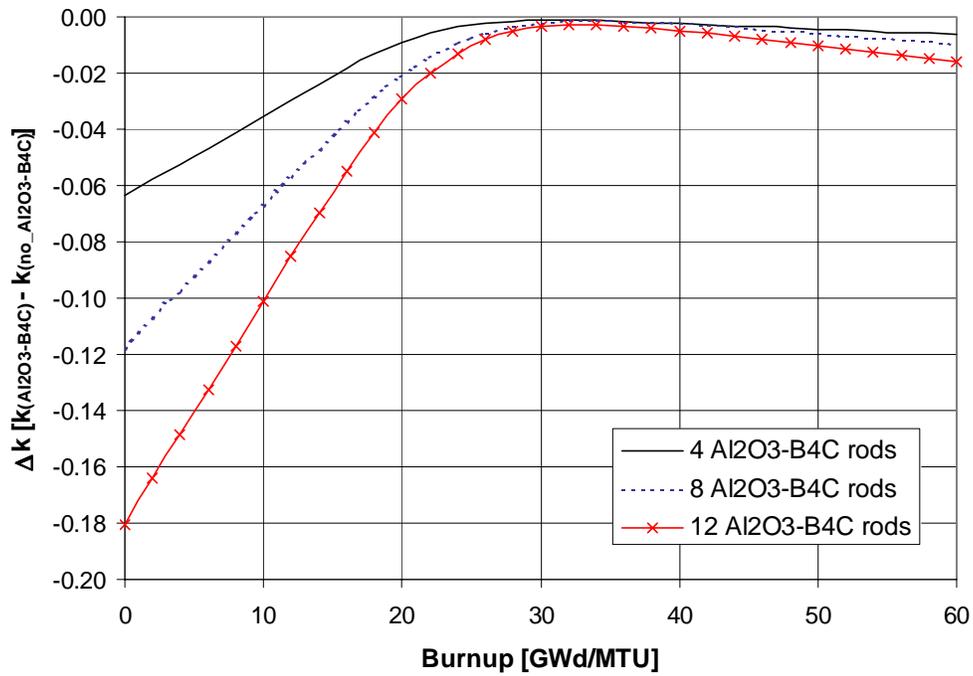Figure 6. Reactivity behavior of PWR fuel with and without Al_2O_3-B_4C (4.0 wt % B_4C) rods present.

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

<u>Additional Studies</u>

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 results in an increase in k and is therefore important from a burnup credit point of view. The results from the three-dimensional (3-D) criticality calculations, performed with the KENO V.a Monte Carlo Code [5] utilizing spent-fuel isotopics from HELIOS, showed that k_{eff} was slightly lower (0.005 Δk) for the case with IBAs present than the case without the IBAs present. A detailed discussion of these studies is available in Ref. [6].

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, the neutron multiplication factor for an assembly with IFBA rods present was found to exceed the neutron multiplication factor for an assembly without IFBA rods. Therefore, neglecting the IBAs in a burnup-credit criticality safety analysis will yield conservative results for assembly designs with UO_2-Gd_2O_3, UO_2-Er_2O_3, or Al_2O_3-B_4C IBA rods and non-conservative results for assembly designs with 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.

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