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Charlotta E. Sanders and John C. Wagner

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

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

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Executive Summary

The Interim Staff Guidance on burnup credit (ISG-8) for pressurized water reactor (PWR) spent nuclear fuel (SNF), issued by the Nuclear Regulatory Commission's (NRC) Spent Fuel Project Office, recommends the use of analyses that provide an "*adequate representation of the physics*" and notes particular concern with the "*need to consider the more reactive actinide compositions of fuels burned with fixed absorbers or with control rods fully or partly inserted*." In the absence of readily available information on the extent of control rod (CR) usage in U.S. PWRs and the subsequent reactivity effect of CR exposure on discharged SNF, NRC staff have indicated a need for greater understanding in these areas. In response, this paper presents results of a parametric study of the effect of CR exposure on the reactivity of discharged SNF for various CR designs (including Axial Power Shaping Rods), fuel enrichments, and exposure conditions (i.e., burnup and axial insertion). The study is performed in two parts. In the first part, two-dimensional calculations are performed, effectively assuming full axial CR insertion. These calculations are intended to bound the effect of CR exposure and facilitate comparisons of the various CR designs. In the second part, three-dimensional calculations are performed to determine the effect of various axial insertion conditions and gain a better understanding of reality. The results from the study demonstrate that the reactivity effect increases with increasing CR exposure (e.g., burnup) and decreasing initial fuel enrichment (for a fixed burnup). Additionally, the results show that even for significant burnup exposures, minor axial CR insertions (e.g., <20 cm) result in an insignificant effect on the k_{eff} of a spent fuel cask.

1. Introduction and Background

The concept of taking credit for the reduction in reactivity due to the fuel burnup is commonly referred to as burnup credit. In contrast to criticality safety analyses that employ the "fresh-fuel assumption," the utilization of credit for fuel burnup necessitates consideration of all possible fuel operating conditions, including exposure to control rods (CRs). In July of 1999, the Spent Fuel Project Office of the U.S. Nuclear Regulatory Commission (NRC) issued an interim staff guidance [1] on burnup credit (ISG-8) that permits partial credit for burnup in pressurized water reactor (PWR) fuel. The recommendations in ISG-8 limit the amount of burnup credit to that available from actinide compositions in irradiated PWR UO_2 fuel up to an assembly-average burnup of 40 GWd/MTU and 5.0 wt % ^{235}U initial enrichment, with a number of associated restricting recommendations. These recommendations include a restriction on the use of burnup credit to assemblies that have not used burnable absorbers and a note of particular concern with the "*need to consider the more reactive actinide compositions of fuels burned with fixed absorbers or with control rods fully or partly inserted*." In the absence of readily available information on the extent of control rod usage in U.S. PWRs and the subsequent reactivity effect of CR exposure on discharged SNF, NRC staff has indicated a need [2] for greater understanding in these areas. In response, this paper presents the results of a parametric study of the effect of CR exposure on the reactivity of discharged SNF for various CR designs (including Axial Power Shaping Rods (APSRs)), fuel enrichments, and exposure conditions (i.e., burnup and axial insertion).

The presence of CRs during depletion hardens the neutron spectrum, resulting in lower ^{235}U depletion and higher production of fissile plutonium isotopes. Enhanced plutonium production and the concurrent diminished fission of ^{235}U due to increased plutonium fission have the effect of increasing the reactivity of the fuel at discharge and beyond. Hence, an assembly exposed to CRs will have a higher reactivity for a given burnup than an assembly that has not been exposed to CRs.

There is a great deal of variability in CR usage and thus quantifying the effect of CRs is not possible in a generic manner. Therefore, analyses were performed for a variety of exposure scenarios to establish greater understanding of the effect of CR exposure of discharged SNF. Many of the scenarios considered are not realistic for current U.S. PWR operations because CRs are typically only inserted into the upper portion of the fuel assemblies (above the active fuel region) during full power operation. Nevertheless, they may be representative of earlier domestic PWR operations as well as PWR operations in other countries. For example, French PWR operating conditions involve long periods of CR insertion for reactor control, low-power operations and load-following [3], and consequently proposed approaches for burnup credit in France include full CR insertion.

The evaluation is performed in two parts. In the first part, two-dimensional (2-D) calculations are performed, simulating full axial CR exposure (i.e., fully inserted). These calculations are intended to 'bound' the effect of CR exposure and facilitate comparisons of the various CR designs. The CRs considered in this paper are the (1) Westinghouse hybrid boron carbide (Ag-In-Cd/B_4C) CR, (2) the Babcock & Wilcox (B&W) Ag-In-Cd CR, and the B&W gray APSR. In the second part of the evaluation, three-dimensional (3-D) calculations are performed to determine the effect of various axial insertion conditions and gain a better understanding of reality for typical current U.S. PWR operations. The calculations focus on the effect of CR exposure on SNF isotopics, and consequently the results consider CRs present during depletion <u>only</u>.

2. Methodology

The 2-D calculations presented in the following section were performed using the HELIOS-1.6 code package [4]. HELIOS is a 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 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, a constant soluble boron concentration of 650 ppm, and a specific power of 60 MW/MTU.

The 3-D criticality calculations were performed with the KENO V.a Monte Carlo code from the SCALE package [5], using spent-fuel isotopics calculated by HELIOS. The KENO V.a calculations used the 238-group cross-section library, based primarily on ENDF/B-V. Unlike the HELIOS criticality calculations, which include all of the actinide and fission product nuclides available in the HELIOS cross-section library, the KENO criticality calculations were performed with subsets of the available nuclides. The use of a subset of actinides in burnup credit calculations is referred to as "actinide-only" burnup credit. The nuclides used here for actinide-only calculations are consistent with those specified in a Department of Energy (DOE) Topical Report on burnup credit [6], with the exception that ^{236}U and ^{237}Np are also included. The use of a subset of actinides and fission products is referred to herein as "actinide + fission product" burnup credit. The fission product nuclides used here for actinide + fission product calculations are consistent with those identified in Table 2 of Ref. [7] as being the most important for criticality calculations.

3. Results and Discussion

The following subsections present a summary of the analyses [8] that have been performed to establish the effect of CR exposure on the reactivity of discharged SNF for various CR designs. The interested reader is referred to Ref. [8] for additional comparisons and detailed CR and fuel design specifications.

Westinghouse Hybrid Boron Carbide (B_4C) CR

The hybrid boron carbide (B_4C) rod cluster control assembly (RCCA), developed by Westinghouse, consists of 24 hybrid (Ag-In-Cd/B_4C) absorber rods [9]. Each CR contains Ag-In-Cd absorber with B_4C absorber pellets stacked on top of the Ag-In-Cd. Calculations were performed with a Westinghouse 17×17 assembly to investigate various CR exposures and gain a better understanding of their impact on reactivity as a function of burnup. Since it is not possible to include the axial variation in absorber material in the HELIOS 2-D lattice model, separate models were developed to compare the effect of the two absorber materials. The first model included only B_4C in CR positions while the second model was based on Ag-In-Cd CRs. Figure 1 illustrates the reactivity behavior of a PWR fuel assembly with and without both Ag-In-Cd and B_4C CRs present as a function of burnup.

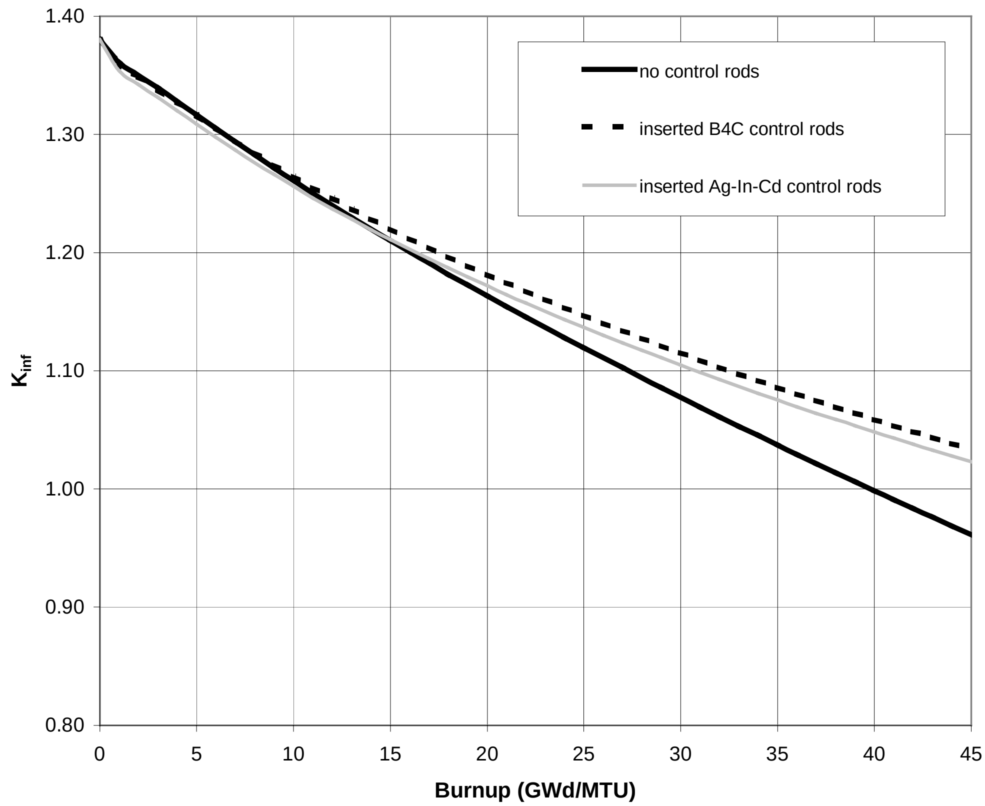

Figure 1. Reactivity behavior (out-of-reactor conditions) of PWR fuel with and without Ag-In-Cd and B_4C CRs present.

Calculations were performed with initial enrichments of 3.0, 4.0, and 5.0 wt % ^{235}U and CRs exposure of 5, 15, 30, and 45 GWd/MTU (full exposure). Three cycles of 15 GWd/MTU per cycle were assumed for the analyses. The Δk values (i.e., differences as compared to uncontrolled assemblies) for the various enrichments as a function of burnup are shown in Figure 2 for B_4C absorber. The results show that the reactivity effect of CRs increases with increasing exposure and decreasing fuel enrichment. Analysis of Ag-In-Cd effects are deferred to the following analysis of a B&W assembly with Ag-In-Cd CRs.

B&W Ag-In-Cd CRs

The Ag-In-Cd RCCA, developed by B&W, consists of 16 Ag-In-Cd cylinders encapsulated in stainless steel cladding [10]. Calculations were performed with a B&W 15×15 assembly with initial enrichment of 4.0 wt % ^{235}U and CRs withdrawn at 5, 15, 30, and 45 GWd/MTU (full exposure). As before, three cycles of 15 GWd/MTU per cycle were assumed for the analysis. The results (Δk as a function of burnup) are shown in Figure 3. Compared to the B_4C absorber considered previously, the reactivity effect of the Ag-In-Cd absorber is smaller.

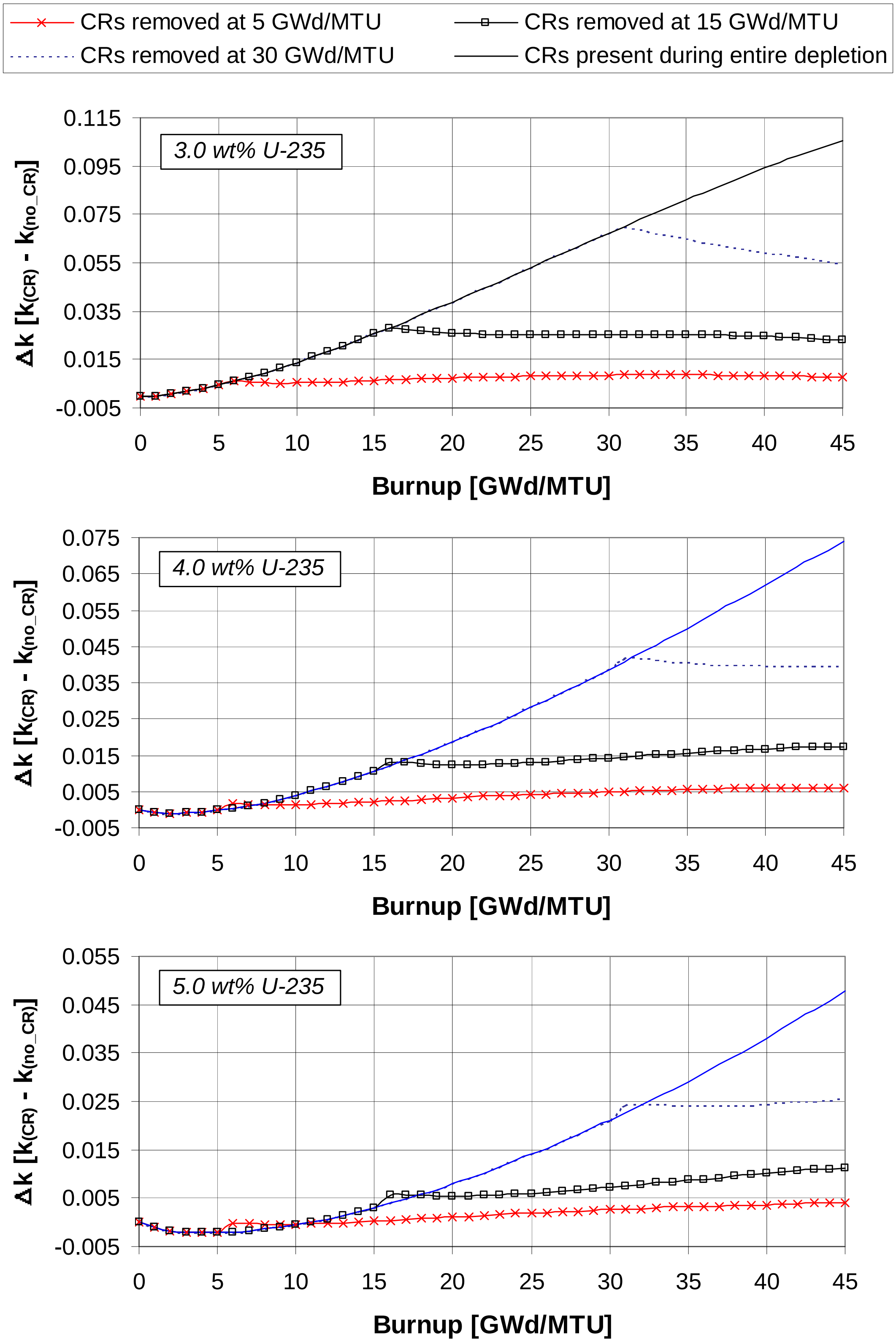

Figure 2. Comparison of Δk values as a function of burnup for various CR exposures with initial fuel enrichment of 3.0, 4.0, and 5.0 wt % ^{235}U, for Westinghouse 17×17 fuel and the B_4C axial segment of the hybrid Ag-In-Cd/B_4C control rods.

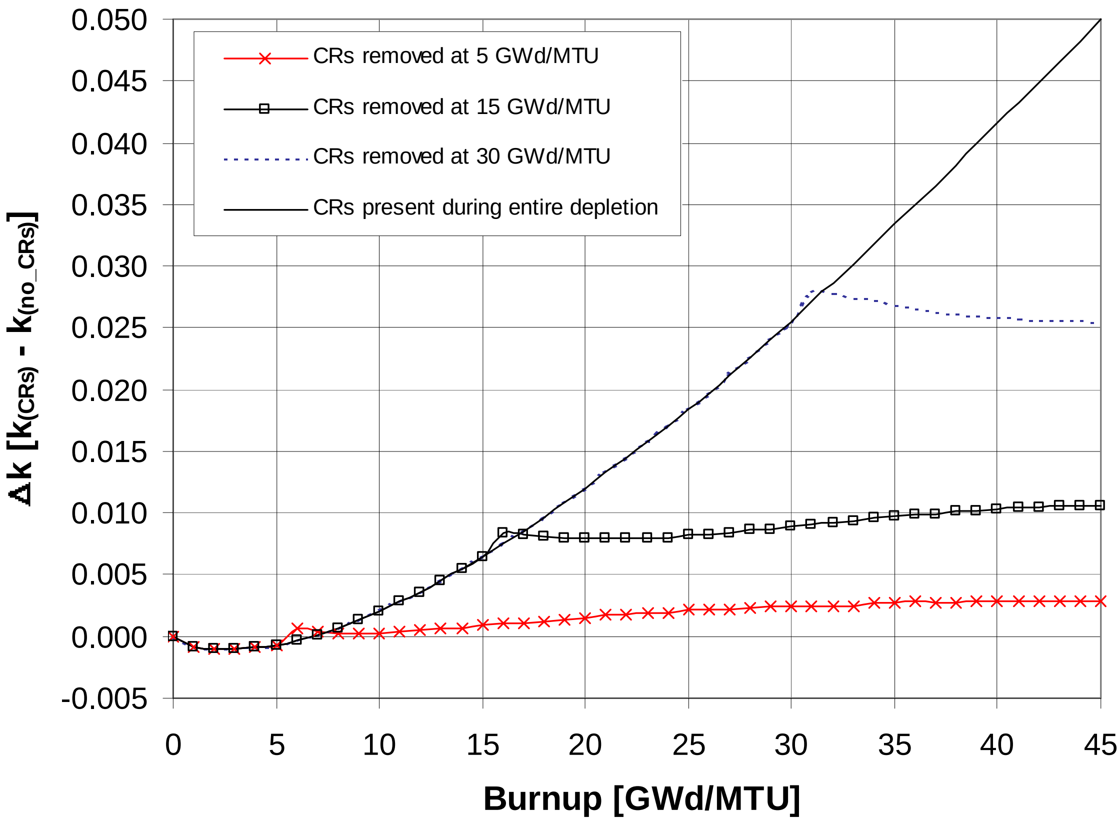

Figure 3. Comparison of Δk values as a function of burnup for various B&W Ag-In-Cd CR exposures with initial fuel enrichment of 4.0 wt % ^{235}U.

Figure 4 compares the Δk for various initial fuel enrichment cases in which the CRs have been fully inserted for 15 GWd/MTU (representing 1 cycle). As mentioned previously, the reactivity effect of the CRs increases with decreasing initial enrichment. Further, it is also interesting to note that the Δk values increase after the CRs are withdrawn for the cases with 4 and 5 wt % ^{235}U enrichment, but decrease for the 3 wt % ^{235}U enrichment case. While the CRs are inserted, they displace moderator and absorb thermal neutrons, significantly hardening the neutron spectrum. The hardened neutron spectrum results in reduced ^{235}U depletion, higher production of fissile plutonium isotopes and increased plutonium fission. Examination of the atom densities of ^{239}Pu and ^{235}U as a function of burnup reveals that the lower the initial ^{235}U enrichment, the greater the ^{239}Pu fission while the CRs are present. Therefore, lower initial ^{235}U enrichments have less net buildup of ^{239}Pu while the CRs are present (relative to higher initial ^{235}U enrichments), because they have an increased rate of ^{239}Pu fission during this period. Note that step-change is not captured in time steps used.

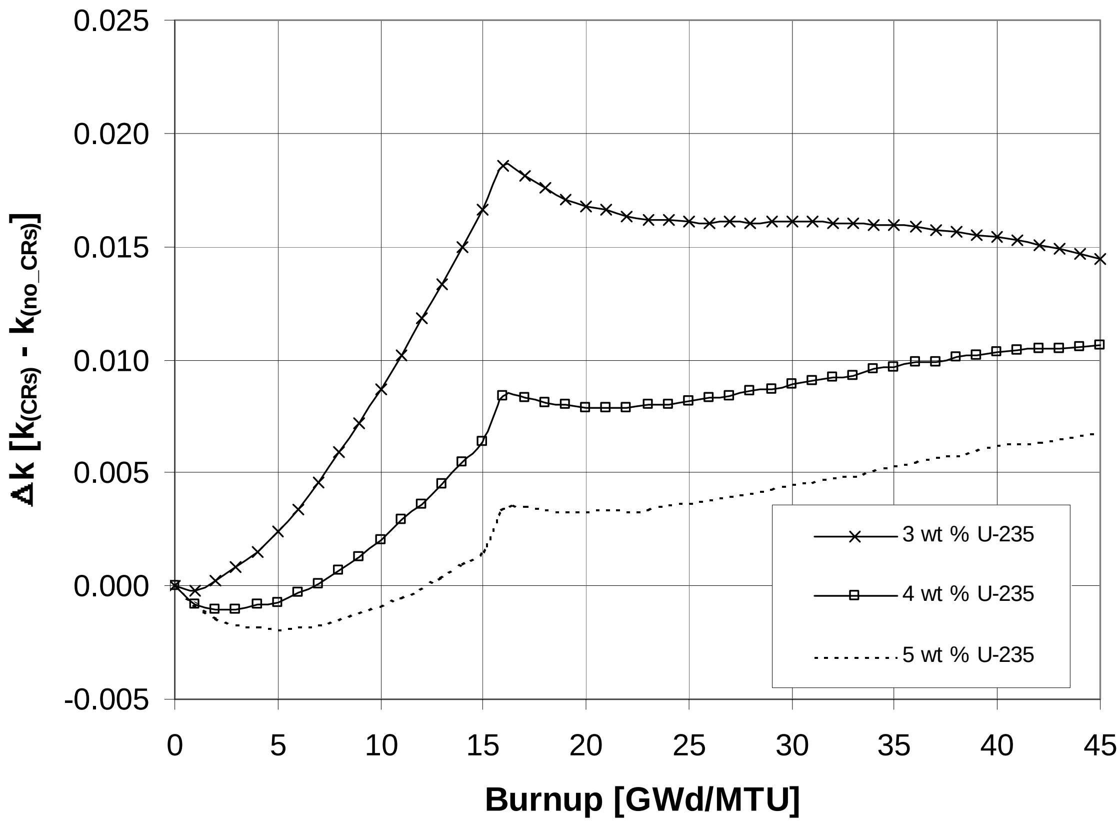

Figure 4. Comparison of Δk values as a function of burnup with B&W Ag-In-Cd CR exposure during the first 15 GWd/MTU (1 cycle) for various initial fuel enrichments.

B&W Gray APSRs

In addition to the previously analyzed Ag-In-Cd CRs, B&W has developed gray part-length APSRs made out of Inconel and stainless steel cladding (the balance of the length is filled with water) [10]. Calculations were performed using a B&W 15×15 assembly with 4.0 wt % ^{235}U initial fuel enrichment and APSRs withdrawn at 5, 15, 30, and 45 GWd/MTU (full exposure). Consistent with the results for the CRs (previously shown), the reactivity effect of the APSRs increases with increasing exposure and decreasing fuel enrichment. However, as displayed by Figure 5, the APSRs have a much smaller reactivity effect compared to the other CR designs, due to the fact that the APSRs do not contain strong thermal neutron absorbing materials.

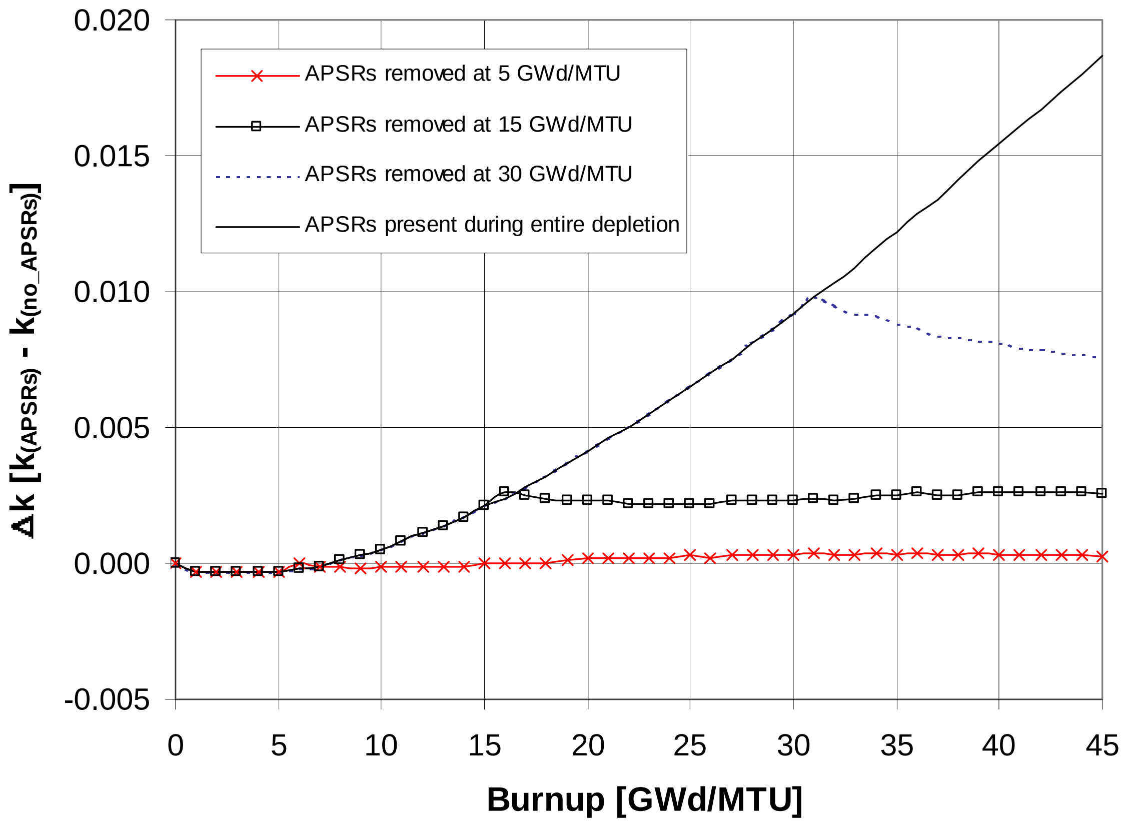

Figure 5. Comparison of Δk values as a function of burnup for various B&W APSR exposures with initial fuel enrichment of 4.0 wt % ^{235}U.

3-D Analyses: Partial-Axial Insertion

3-D calculations were performed to establish the reactivity effect of CR exposure as a function of axial insertion. For this analysis, the generic 32 PWR-assembly burnup credit (GBC-32) cask was used. A physical description of the cask is provided in Ref. [11]. For each CR design considered, a series of calculations were performed to determine the effect of various axial depths of CR insertion. The axial distribution was not included because it is considered in the selection of bounding axial burnup profile(s) [6]. Instead, this analysis examines the effect of CR insertion on reactivity due to spectral hardening. The criticality models included isotopics from depletion calculations with CRs present (in the axial region representing CR insertion) and isotopics from depletion calculations without CRs present (in the remaining axial region). As the results of the series of calculations for the various CR design were similar, only the results from the calculations performed with the Westinghouse 17×17 assembly with the hybrid (Ag-In-Cd/B_4C) CRs is presented here. The axial variation in CR absorber material, B_4C absorber in the top part of the CR (approximately 260 cm) and Ag-In-Cd absorber in the bottom part (approximately 102 cm), were modeled. The k_{eff} values for actinide-only and actinide + fission product burnup credit in the GBC-32 cask with various axial CR exposures are shown in Figure 6. The results correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has been exposed to Westinghouse hybrid B_4C/Ag-In-Cd rods for 5, 15 and 45 GWd/MTU, respectively, while accumulating a discharge burnup of 45 GWd/MTU. The KENO V.a model consists of

18 axial zones nodes with uniform height (approximately 20 cm/per zone) and uniform axial burnup. The results show that even for significant burnup exposures, minor axial CR insertions (e.g., <20 cm) result in an insignificant effect on the k_{eff} of the cask.

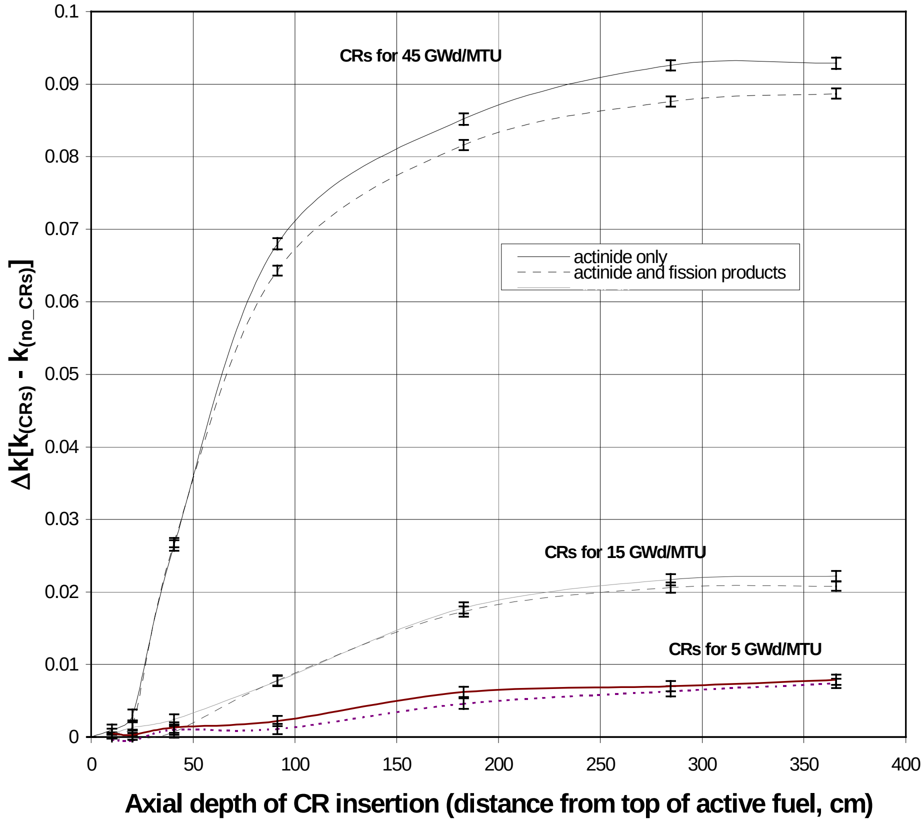

Figure 6. Δk values in the GBC-32 cask (45 GWd/MTU, zero cooling) versus axial CR insertion, as calculated with KENO V.a based on isotopics from HELIOS for actinide-only and actinide + fission product burnup credit. The results are for Westinghouse 17 × 17 fuel with 4.0 wt % ^{235}U initial enrichment and hybrid Ag-In-Cd/B_4C CRs. Error bars correspond to 1σ uncertainties in the Δk values.

4. Conclusions

The analyses presented here provide an understanding of the effect of CR exposure on the reactivity of discharged SNF. The results from the analyses demonstrate that the effect of CRs on Δk increases with increasing CR exposure and decreasing fuel enrichment. The 2-D cases established an upper bound on the Δk effect of CRs with burnup exposure, fuel enrichment, and absorber material. However, and more importantly in terms of practical considerations for current U.S. PWR operations, 3-D analyses were also described in which the reactivity effect of CRs is assessed as a function of axial CR insertion. These calculations show that even for significant burnup exposures, minor axial CR insertions (e.g., <20 cm) result in an insignificant effect on the k_{eff} of a burnup credit cask. Consequently, it is concluded that, based on the assumption that U.S. PWRs do not use CRs to a significant extent (i.e., CRs are not inserted deeper than the top ~20 cm of the active fuel and CRs are not inserted for extended burnups), the effect of CRs on discharge reactivity is relatively small (less than 0.2% Δk).

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