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J. C. Wagner and C. V. Parks

Oak Ridge National Laboratory,*
P. O. Box 2008,
Oak Ridge, TN 37831-6370
(865) 241-3570

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J. C. Wagner and C. V. Parks

Oak Ridge National Laboratory*
P.O. Box 2008
Oak Ridge, TN 37831-6370
Telephone: (865) 241-3570
FAX: (865) 576-3513
Email: wagnerjc@ornl.gov

1 INTRODUCTION

The concept of taking credit for the reduction in reactivity due to fuel burnup is commonly referred to as *burnup credit*. The reduction in reactivity that occurs with fuel burnup is due to the change in concentration (net reduction) of fissile nuclides and the production of actinide and fission-product neutron absorbers. The change in the concentration of these nuclides with fuel burnup, and consequently the reduction in reactivity, is dependent upon the depletion environment (e.g., the neutron spectrum). Therefore, the utilization of credit for fuel burnup necessitates consideration of the fuel operating conditions, including exposure to burnable absorbers.

Burnable absorbers may be classified into two distinct categories: (1) Burnable Poison Rods (BPRs) and (2) Integral Burnable Absorbers. BPRs are rods containing neutron absorbing material that are inserted into the guide tubes of a PWR assembly during normal operation and are commonly used for reactivity control and enhanced fuel utilization. In contrast to BPRs,

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integral burnable absorbers refer to burnable poisons that are a non-removable or integral part of the fuel assembly once it is manufactured. An example of an integral burnable absorber is the Westinghouse Integral Fuel Burnable Absorber (IFBA) rod, which has a coating of zirconium diboride (ZrB_2) on the fuel pellets. Although integral burnable absorbers are also common in current PWR fuel designs, this paper will focus on the effect of BPRs only.

The Interim Staff Guidance¹ on burnup credit issued by the Nuclear Regulatory Commission's Spent Fuel Project Office restricts 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. Consequently, this paper examines the effect of BPRs on reactivity for various BPR designs and exposure conditions.

2 BPR DESIGNS AND OPERATIONAL PRACTICES

The primary Westinghouse and B&W BPR designs were considered in this paper. Westinghouse has manufactured two main types^{2,3} of BPRs: (1) Burnable Absorber Assemblies (BAAs) and (2) Wet Annular Burnable Absorbers (WABAs). The BAAs utilize borosilicate glass (B_2O_3 - SiO_2 with 12.5 wt % B_2O_3) in the form of Pyrex tubing as a neutron absorber with a void central region⁴ and SS304 cladding. WABAs are similar to BAAs, but utilize annular pellets of Al_2O_3 - B_4C (14.0 wt % B_4C) as the neutron absorber, have a wet (water-filled) central region,⁵ and Zircaloy cladding. Configurations of BAAs and WABAs have been identified with varying (4-24) numbers of rods.^{2,3} B&W has primarily manufactured a single BPR design,^{2,3} which consists of solid rods containing Al_2O_3 - B_4C clad in Zircaloy. Unlike the Westinghouse design, the number of BPRs per assembly is fixed and the weight percent of B_4C in each BPR is

variable. Actual plant data in ref. 6 shows variations in B₄C loading from 0.2 to 2.1 weight percent.

Burnable poison rod assemblies (BPRAs) are typically inserted into a PWR fuel assembly during its first cycle in the reactor core and the actual number (Westinghouse) or poison loading (B&W) of BPRs within a BPRA is variable, typically less than the maximum possible. Due to the depletion of the neutron absorbing material, BPRAs are often (but not always) withdrawn after one-cycle residence in the core.

3 EFFECT OF BPRS ON REACTIVITY

The presence of BPRs during depletion hardens the neutron spectrum due to removal of thermal neutrons by capture in ¹⁰B and by displacement of moderator, resulting in lower ²³⁵U depletion and higher production of fissile plutonium isotopes. Enhanced plutonium production and the concurrent diminished fission of ²³⁵U due to increased plutonium fission have the effect of increasing the reactivity of the fuel at discharge and beyond. Consequently, an assembly exposed to BPRs will have a higher reactivity for a given burnup than an assembly that has not been exposed to BPRs.

For each of the BPR designs mentioned, spent fuel isotopics were calculated for possible loading variations. SAS2H⁷ depletion calculations were performed assuming the BPRs were present during (1) the first cycle of irradiation, (2) the first two cycles of irradiation, and (3) the entire irradiation period (i.e., all three cycles). For comparison purposes, isotopics were also calculated assuming no BPRs present. These four sets of isotopics were then used in individual CSAS1X⁷ calculations to determine the reactivity effect of each BPR design as a function of burnup for out-of-reactor conditions at burnup steps of 1 GWd/MTU and zero cooling time. Note

that the criticality calculations were based on an infinite array of spent fuel pin cells using isotopics from the various BPR depletion cases, and thus, the effect of the BPRs is determined based on their effect on the depletion isotopics alone (i.e., the BPRs are not included in the criticality models).

Figure 1a plots the reactivity differences (Δk values relative to the no BPR condition) as a function of burnup for the Actinide-Only condition. The nuclides used here for Actinide-Only calculations are consistent with those specified in the DOE Topical,⁸ with the exception that ²³⁶U and ²³⁷Np are also included. The isotopics used in the criticality calculations correspond to spent fuel with 4.0 wt % ²³⁵U initial enrichment that has been exposed to Westinghouse WABA rods during depletion. For the purpose of the depletion calculations, 3 cycles of 15 GWd/MTU per cycle were assumed. The results shown in Fig. 1a demonstrate that the reactivity effect increases with BPR exposure (burnup and number of BPRs present) and that calculations based on continuous exposure during the entire depletion yield higher (more conservative) reactivity than analyses based on actual/typical one-cycle exposures. Figure 1b shows results for the same conditions plotted in Figure 1a, with the exception that the major fission products are included. The reactivity behavior is shown to be very similar to that of the Actinide-Only condition.

For comparison of the effect of the various BPR designs, calculations have also been performed for the Westinghouse BAAs and the B&W BPRs. The results are very similar to those shown in Fig. 1 for the Westinghouse WABAs.⁹ Since the B₄C weight percent is known to vary in the B&W BPRs,⁶ the reactivity effect of varying the B₄C poison loading was also investigated and verified to increase with poison loading.⁹ Finally, the reactivity effect of BPRs was found to increase with decreasing initial enrichment (for a fixed burnup).⁹

3.1 Reactivity Effect of BPRs for a Rail-Type Cask

The reactivity effect of BPRs within a realistic high-capacity rail-type cask has also been examined and quantified. For this analysis, the Generic 32 PWR-assembly Burnup Credit (GBC-32) cask¹⁰ loaded with Westinghouse 17×17 OFA assemblies was used. The GBC-32 design was developed to provide a reference cask configuration that is representative of typical high-capacity rail casks being considered by industry.

The cask criticality calculations were performed with the KENO V.a Monte Carlo code⁷ using the SCALE 238-group cross-sections based on ENDF/B-V. The cross-sectional view of the GBC-32 cask shown in Figure 2 is based on the KENO V.a model. The BPRAs are not included in the KENO V.a criticality model. Isotopics were calculated using the SAS2H sequence.⁷

The k_{eff} values for Actinide-Only and Actinide + Fission Product burnup credit in the GBC-32 cask, assuming uniform axial burnup, for various BPR exposures are listed in Table 1. The results correspond to spent fuel with 4.0 wt % ²³⁵U initial enrichment that has been exposed to Westinghouse WABA rods while accumulating a burnup of 45 GWd/MTU and 5-year cooling time. For the purpose of the depletion calculations, 3 cycles of 15 GWd/MTU per cycle are assumed. The relative behavior is very similar to that exhibited for an infinite array of fuel pins.

To determine the impact of incorporating the axial burnup distribution, k_{eff} values were also calculated for the GBC-32 cask for various BPR exposures with the axial burnup distribution included. The results reveal that the inclusion of the axial burnup distribution reduces the reactivity increase associated with the BPRs. This is due to the fact that the lower burnup regions near the ends, that control the reactivity of the fuel when the axial burnup

distribution is included, have less burnup, and thus less burnup exposure to the BPRs (than the average).

3.2 Verification of the SAS2H Depletion Isotopics

A SAS2H fuel assembly model is limited to a one-dimensional radial model with a single smeared fuel region. Geometric modeling approximations are made in an effort to achieve a reasonable assembly-average neutron energy spectrum during the depletion process. However, the presence of BPRs challenges the SAS2H modeling capabilities. Therefore, for a select number of cases, isotopics were also calculated with the HELIOS code package¹¹ for verification of the SAS2H isotopics. HELIOS is a two-dimensional, generalized-geometry transport theory code based on the method of collision probabilities with current coupling. The reactivity differences (Δk values relative to the no BPR condition) as a function of burnup based on isotopics calculated by SAS2H and HELIOS were compared and found to be within a few tenths of a percent, with SAS2H isotopics predicting slightly larger reactivity effects. Further, very good agreement between calculated k_{inf} values based on isotopics from SAS2H and HELIOS was achieved.

4 CONCLUSIONS

The reactivity effect of BPRs increases nearly linearly with burnup and is dependent upon the number and poison loading of the rods and the initial fuel enrichment. Although variations are observed for the various BPR designs, maximum reactivity increases have been found to be ~1-3 percent when maximum BPR loading and exposure time are assumed for typical initial enrichment and discharge burnup combinations.

Based on the analysis summarized in this paper, guidance for an appropriate approach for calculating bounding spent nuclear fuel isotopic data for assemblies exposed to BPRs may be developed. For example, assuming maximum BPR exposure during depletion would be a simple, conservative approach to bound the reactivity effect of BPRs; where maximum BPR exposure may be defined as the maximum possible number of BPRs with the most bounding BPR design (i.e., most bounding geometric design and maximum possible poison loading) for the entire depletion.

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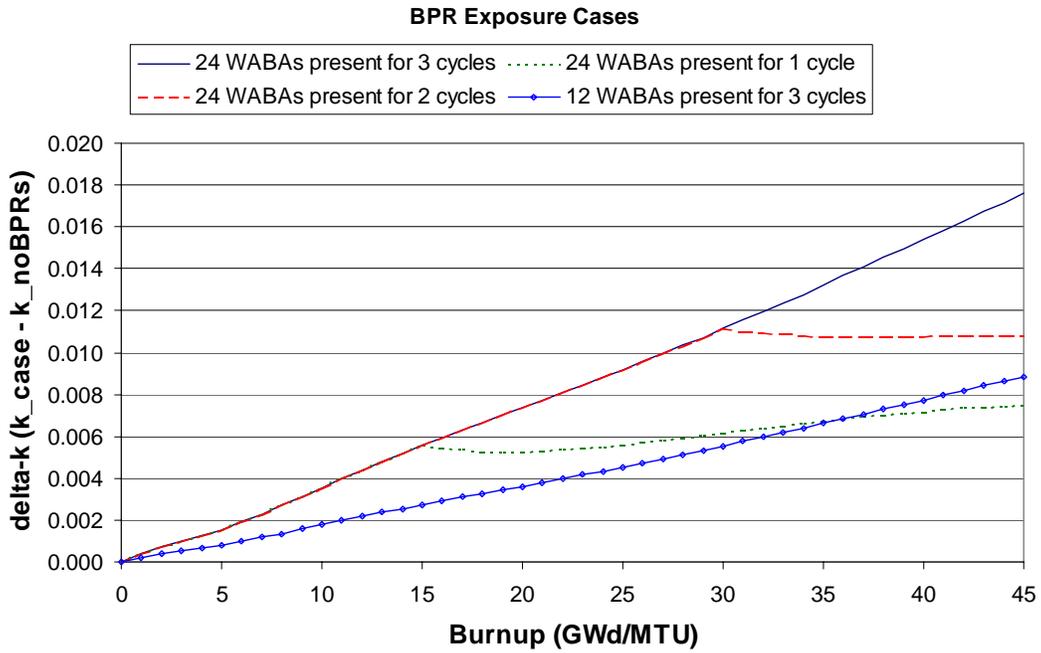
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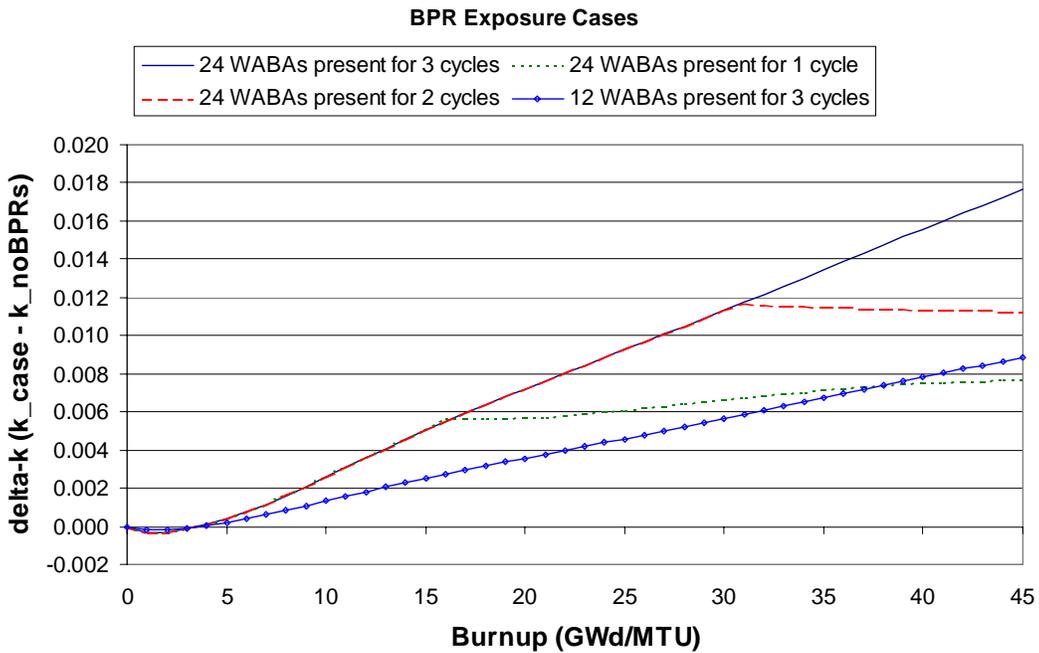
Table 1. Reactivity Effect of Various BPR Exposures in the GBC-32 Cask
(45 GWd/MTU, 5-year cooling)

Number of WABAs present	Number of cycles of exposure [†]	KENO Va k_{eff}	Standard deviation	Difference from no BPRs (k_case – k_noBPRs)	Standard deviation in Difference
Actinide-Only					
0	3	0.89174	0.00034	reference	---
12	1	0.89770	0.00038	0.00596	0.00051
12	2	0.89906	0.00037	0.00732	0.00050
12	3	0.90044	0.00035	0.00870	0.00049
24	1	0.90164	0.00040	0.00990	0.00052
24	2	0.90521	0.00036	0.01347	0.00050
24	3	0.90953	0.00039	0.01779	0.00052
Actinides + Fission Products					
0	3	0.79781	0.00035	reference	---
12	1	0.80244	0.00036	0.00463	0.00050
12	2	0.80389	0.00036	0.00608	0.00050
12	3	0.80695	0.00037	0.00914	0.00051
24	1	0.80581	0.00035	0.00800	0.00049
24	2	0.80996	0.00031	0.01215	0.00047
24	3	0.81556	0.00032	0.01775	0.00047

[†] One exposure cycle corresponds to a burnup of 15 GWd/MTU.



(a) Actinide-Only burnup credit



(b) Actinide + Fission Product burnup credit

Fig. 1. Reactivity differences (Δk values relative to the no BPR condition) as a function of burnup for various BPR exposures. The results correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has been exposed to Westinghouse WABA rods (3 cycles of 15 GWd/MTU per cycle were assumed).

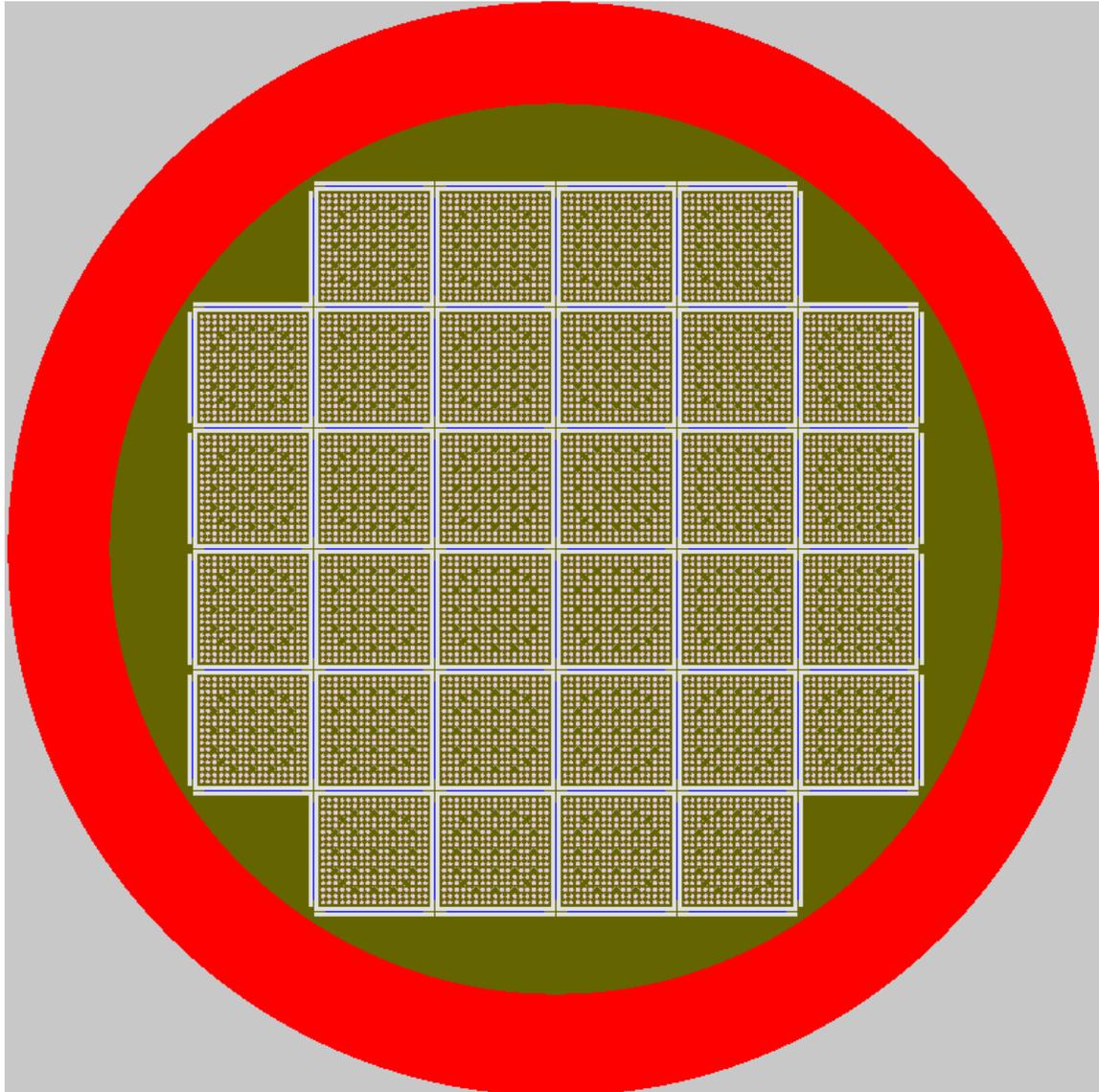


Fig. 2. KENO Va calculational model of the PWR 32-assembly Generic Burnup Credit cask (GBC-32) loaded with Westinghouse 17×17 OFA assemblies.