EFFECTS OF BURNABLE ABSORBERS ON PWR SPENT NUCLEAR FUEL

Patrick M. O'Leary, Dr. Michelle L. Pitts
Framatome ANP

ABSTRACT

Burnup credit is an ongoing issue in designing and licensing transportation and storage casks for spent nuclear fuel (SNF). To address this issue, in July 1999, the U.S. Nuclear Regulatory Commission (NRC), Spent Fuel Project Office, issued Interim Staff Guidance-8 (ISG-8), Revision 1 (1) allowing limited burnup credit for pressurized water reactor (PWR) SNF to be used in transport and storage casks. However, one of the key limitations for a licensing-basis analysis as stipulated in ISG-8, Revision 1 is that "burnup credit is restricted to intact fuel assemblies that have not used burnable absorbers." Because many PWR fuel designs have, for more than 20 years, incorporated burnable-absorber rods this restriction places an unnecessary burden on the commercial nuclear power industry. This paper summarizes the effects of in-reactor irradiation on the isotopic inventory of PWR fuels containing different types of burnable absorbers (BAs). The work presented is illustrative and intended to represent typical magnitudes of the reactivity effects from depleting PWR fuel with different types of burnable absorbers.

INTRODUCTION

Two general types of burnable absorbers (BAs) are used with PWR fuel: integral burnable absorbers (IBAs) and burnable poison rods (BPRs). IBAs are non-removable, neutron-absorbing materials used as components of a fuel assembly. BPRs, however, are rods that contain neutron-absorbing materials that can be inserted in PWR assembly guide tubes. Both types of BAs can be used to control core reactivity and local power peaking and optimize fuel utilization. In general, both types of BAs are designed to function during the first cycle of irradiation of a fresh, unirradiated fuel assembly. After one cycle of irradiation, the BPRs are typically removed from the fuel assembly allowing primary coolant to occupy the guide tube volume displaced by the BPRs. In the case of IBAs, the rods remain in the fuel assembly throughout its lifetime and usually account for a small reactivity penalty at end of life, due to incomplete consumption of the neutron-absorber material.

GENERAL PWR FUEL TYPES

Fuel assemblies for B&W designed reactors (MkB fuel) comprise a 15x15 array of fuel rods with 16 guide tubes and a central instrument tube. The guide tubes accommodate either control-rod fingers or BPRs depending on the location of the assembly in the core and the specific fuel design.

Westinghouse-type fuel assemblies can comprise 14x14, 15x15, or 17x17 arrays of fuel rods, depending on the plant design. The 14x14 and 15x15 arrays each contain 20 guide tubes and a central instrument tube. The 17x17 array contains 24 guide tubes and a central instrument tube. Like the MkB fuel, the guide tubes can accommodate either control-rod fingers or BPRs depending on the assembly location in the core and the specific fuel design.

Combustion Engineering (CE)-type fuel assemblies comprise a 14x14 or a 16x16 array of fuel rods depending on plant design. Each fuel design contains five large guide tubes; one centrally located with the other four symmetrically located in each quadrant of the lattice. Each guide-tube location occupies the space of four fuel rods, and is water filled when the control cluster is removed. To date, BPRs have not been used in CE fuel.

INTEGRAL BURNABLE ABSORBERS

PWR fuel uses several different types of integral burnable absorbers. For example, in some IBAs, neutron absorbers such as gadolinia (Gd_2O_3) or erbia (Er_2O_3) are mixed directly with the uranium dioxide (UO_2) fuel in select rod locations within an assembly. The Westinghouse-designed Integral Fuel Boron Absorber (IFBA) rods contain uranium pellets with a thin coating of zirconium diboride (ZrB_2). Other integral absorbers, such as boron carbide (B_4C), are mixed in alumina-based (Al_2O_3) pellets and placed in rods that replace uranium fuel rods in some CE-designed fuel assemblies.

Westinghouse, and CE-type fuel assemblies have all used gadolinia in IBAs for some specific fuel designs. Presently, only Westinghouse-fabricated fuel assemblies use IFBA fuel rods.

Until recently, IBA rods were generally loaded symmetrically in a fuel assembly with similarly loaded assemblies symmetrically located within the core. More recently, aggressive core designs have been incorporating asymmetric IBA loadings to "fine-tune" fuel assembly local power peaking concerns. Fuel designs using gadolinia may incorporate as many as 20 Gd_2O_3 - UO_2 fuel rods in a single fuel assembly. Fuel designs using erbia may incorporate approximately 90 Er_2O_3 - UO_2 fuel rods in a single fuel assembly. As many as one-half of the rods in some Westinghouse fuel assemblies may contain IFBA rods. Finally, some CE-designed fuel assemblies contain B_4C – Al_2O_3 rods that may replace approximately 20 uranium fuel rods. The fuel vendors usually consider the exact details of poison concentration, the number of poison rods and rod locations to be proprietary information. For this reason, the concentrations have been omitted and only general numbers of poison rods have been described to give a relative idea of the possible variations in designs.

BURNABLE POISON RODS

Several general types of BPRs have been used in PWR fuel. Framatome Cogema Fuels (FCF) uses BPRs composed of B_4C – Al_2O_3 pellets contained in zircaloy tubing. The Westinghouse configuration for BPRs uses hollow Pyrex glass (B_2O_3 - SiO_2) tubing sealed in stainless steel cladding. More recently, Westinghouse has used wet annular burnable absorbers (WABAs) that are similar to the Pyrex absorbers but use hollow B_4C – Al_2O_3 pellets clad in zircaloy with a central, flow-through, water region for enhanced neutron moderation.

In all cases, the BPR rodlets are attached to an assembly (BPRA) "spider" that can be mechanically attached to the fuel assembly upper tie plate, securing it in position during core operation. During a refueling outage, the spider can be removed from a fuel assembly using remote-handling tools before the assembly is returned to the core for another cycle of irradiation. FCF BPR clusters comprise between 4 and 16 rodlets. Westinghouse BPR clusters comprise between 4 and 20 rodlets for 14x14 and 15x15 arrays, or 24 rodlets for 17x17 arrays. It is uncommon for a BPRA to remain in a fuel assembly for more than one cycle of irradiation.

ANALYSES

PWR fuel assemblies containing typical loadings of gadolinia, erbia, boron carbide-alumina and IFBA rods have been analyzed to investigate their neutronic effects on PWR SNF. Each infinite-array lattice, poisoned and unpoisoned, was depleted with CASMO-3 (3) under normal, hot-operating conditions. Three cycles of 15 GWd/mtU exposure each were used to represent the depletion history effects on the fuel. Restart calculations were then run at each burnup point removing the xenon, setting the soluble boron to 0 ppmB, and the fuel and moderator temperatures to 300 K to simulate cold-storage cask conditions. No radioactive decay periods were accounted for in the analyses. However, isotopic decay will be considered at a later date for disposal purposes.

PWR fuel containing the maximum number of Pyrex and WABA BPRs have been analyzed to investigate their neutronic effects on PWR SNF. These arrays were depleted using the same method as that used for the IBA analyses. In addition, the BPRs were removed from the fuel after one and two cycles of depletion. After being removed, the BPRs were replaced with water and depleted to end-of-life conditions. To evaluate their effect on fuel assembly isotopic inventory, the BPRs were not included in the restart calculations.

RESULTS

Plots of the results of the IBA (Figures 1-3) and BPR (Figure 4) analyses show the reactivity difference of "poisoned" and "unpoisoned" as a function of burnup for fuel with the same initial enrichment. In all cases analyzed, the results indicate that the reactivity effect from burnable absorbers on PWR SNF is generally small, and well behaved (smoothly varying as a function of fuel burnup), and can be well characterized.

The k-infinity for gadolinia-bearing fuel is always less than that for the non-gadolinia fuel. The difference, as shown in Figure 1, is less than 0.2 % Δk near 45 GWd/MTU.

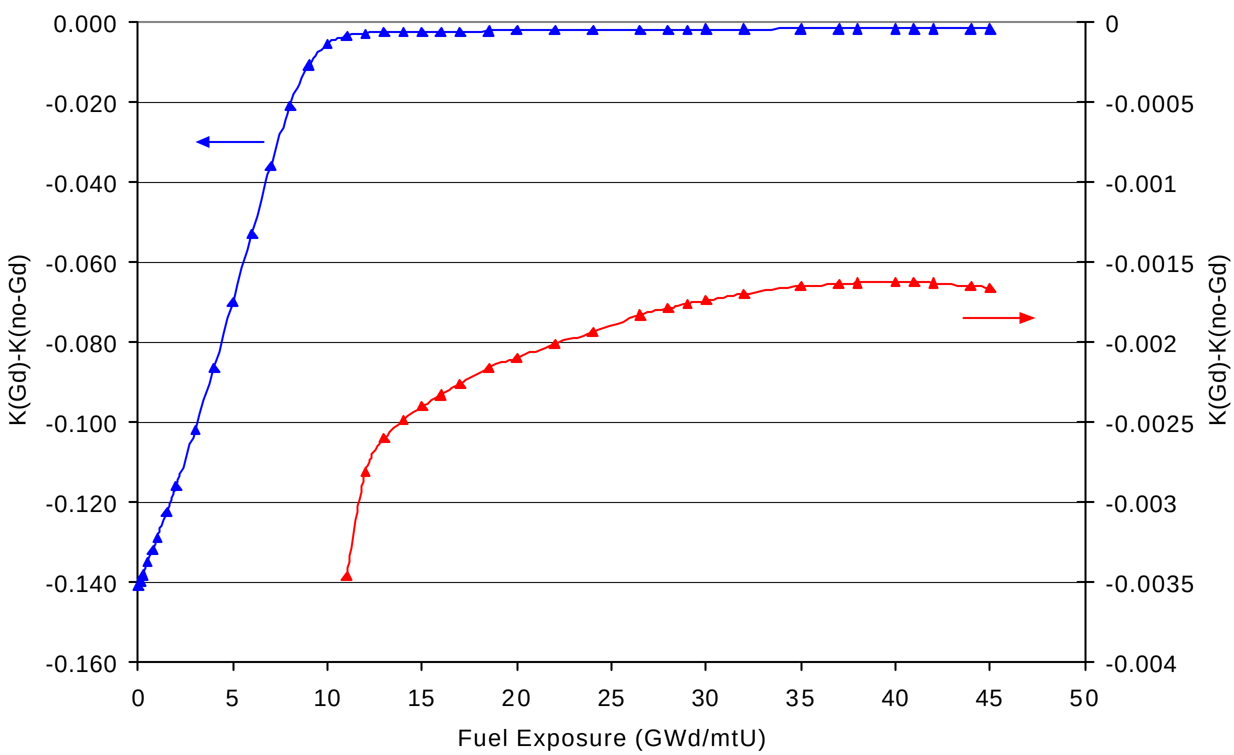

Fig. 1. Gadolinia Neutron-Absorber Rod Reactivity Effects on PWR SNF

The k-infinity for erbia-bearing fuel is also always less than that for the non-erbia fuel. The difference, as shown in Figure 2, is approximately 1 % Δk near 45 GWd/mtU.

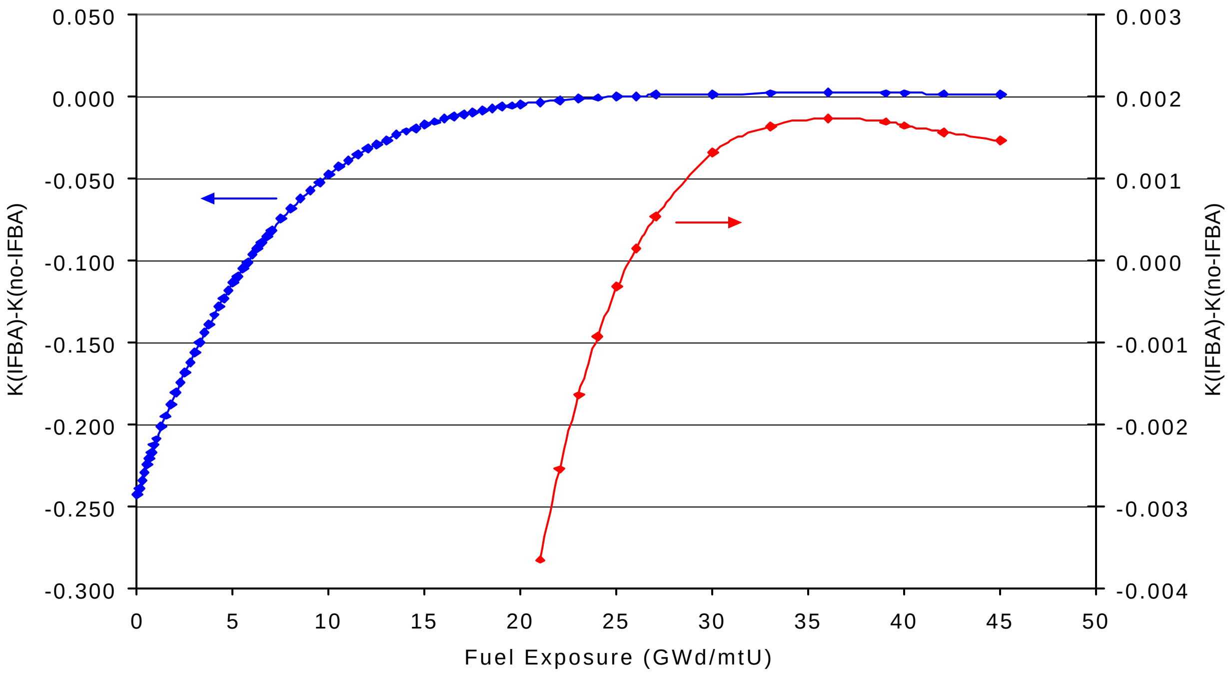

Fig. 2. Erbia Neutron-Absorber Rod Reactivity Effects on PWR SNF

The k-infinity for IFBA-bearing fuel became greater than that for the non-IFBA fuel by less than 0.2 % Δk near 35 GWd/mtU where it began to decrease with further burnup, as shown in Figure 3.

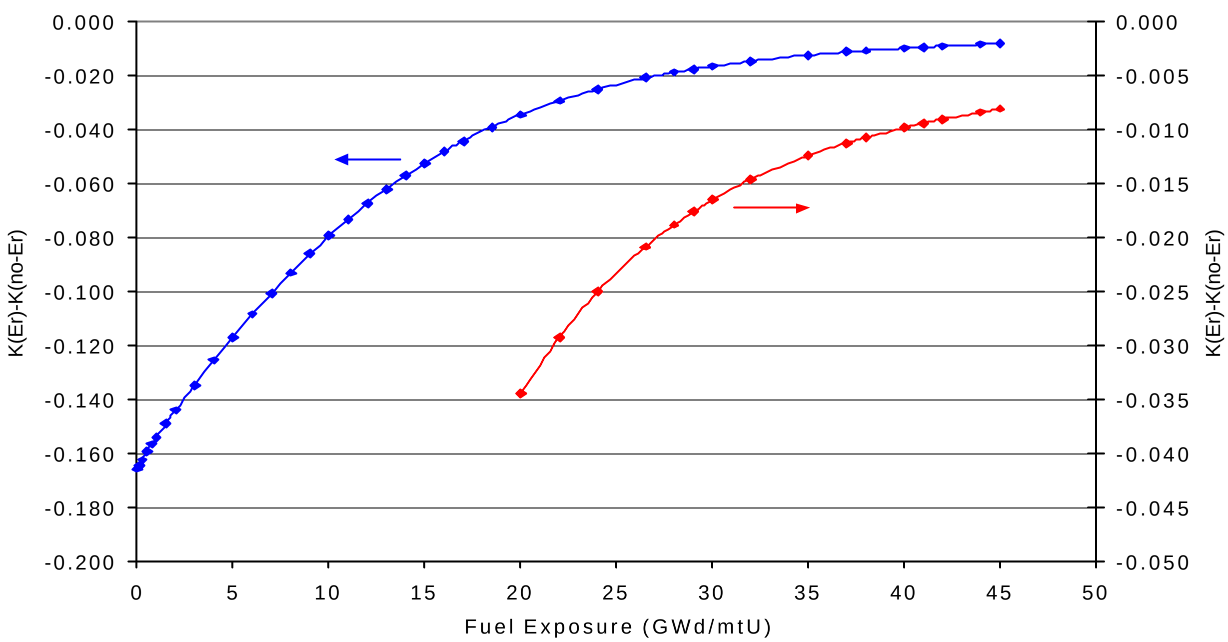

Fig. 3. IFBA Rod Reactivity Effects on PWR SNF

The case for B_4C-Al_2O_3 rods is different than the other IBA cases because the poison rods actually replace uranium fuel rods in the assembly. A 16x16 CE-design fuel assembly containing 12 B_4C-Al_2O_3 rods was analyzed using the same depletion method used for the other IBAs. The difference in k-infinity varied, over the complete depletion range of 0 to 45 GWd/mtU from approximately –0.14 Δk to almost –0.002 Δk.

For Pyrex BPRs, the effect on k-infinity is approximately 2 % Δk at the time of removal and diminishes slightly with further irradiation. For WABA BPRs, the effect on k-infinity is less than 1 % Δk at the time of removal and diminishes slightly with further irradiation. Both Pyrex and WABA results are plotted in Figure 4 and show similar neutronic behavior.

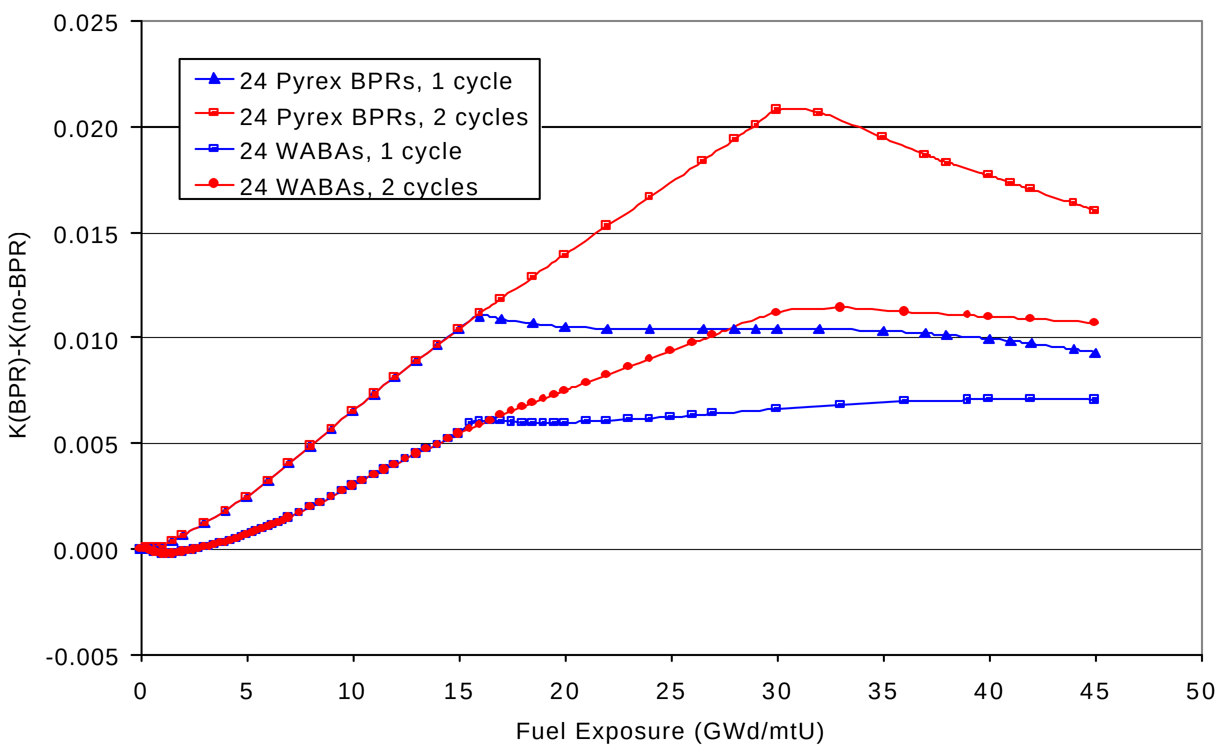

Fig. 4. Pyrex and WABA Reactivity Effects on PWR SNF

CONCLUSIONS

This paper has given an overview of the effects of in-reactor irradiation on the isotopic inventory of PWR fuels containing different types of burnable absorbers (BAs). The work presented illustrates typical magnitudes of the reactivity effects from depleting PWR fuel with the various types of burnable absorbers used to date. It is believed, from a phenomenological basis, that specific BA fuel designs will behave similarly. Because there appears to be a negative reactivity impact on SNF that used gadolinia or erbia, it may be conservative to ignore those neutron absorbers when performing depletion calculations for burnup credit applications. This approach would of course need to be validated as a part of a criticality methodology seeking approval from a licensing authority. In addition, since the neutronic behavior of other types of BAs can be predicted, their effects can be accounted for in the development of a criticality methodology involving them.

Given the results shown above, consideration should be given to removing the restriction on burnup credit for PWR fuel assemblies that have used burnable absorbers.

ACKNOWLEDGEMENTS

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