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New burnable absorber for long-cycle low boron operation of PWRs

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ABSTRACT

This paper presents a new high performance burnable absorber (BA) design for advanced Pressurized Water Reactors (PWRs) aiming for a long-cycle operation with a low soluble boron concentration. The new BA consists of a UO_2–$^{157}Gd_2O_3$ rod covered with a thin layer of $Zr^{167}Er_2$. A key feature of this new BA is that enriched isotopes, ^{157}Gd and ^{167}Er, are used as absorber materials. Since the high absorption cross section of ^{157}Gd can reduce the mass fraction of Gd_2O_3 in UO_2–Gd_2O_3, the thermal margin of fuel rods will increase with higher heat conductivity. Also, the ^{157}Gd transmutes into ^{158}Gd by neutron absorption and therefore the residual penalty at the end of cycle (EOC) will decrease. Since ^{167}Er has a resonance near the thermal neutron energy region, the moderator temperature coefficient (MTC) will become more negative and the control rod worth will increase. These advantages of the new BA are demonstrated with three verification cases: a 17×17 Westinghouse (WH) type fuel assembly, a 16×16 Combustion Engineering (CE) type fuel assembly, and an OPR-1000 equilibrium core.

1. Introduction

There are two primary utility requirements for GEN III+ Pressurized Water Reactors (PWR) (Berbey and Rousselot, 2004). The first one is a long cycle operation. Table 1 from reference Ozer and Edsinger (2001) shows the relationship between cycle length and core characteristics such as initial fuel loading, amount of burnable absorber (BA), critical boron concentration, and the moderator temperature coefficient (MTC). It can be noted that, for an increase of cycle length from 12 months to 24 months, the number of fuel assemblies (FAs) needs to increase by more than twice. The average ^{235}U enrichment in the core also increases by about 0.4 w/o (Ozer and Edsinger, 2001). When the amount of fuel increases, the amount of BA and the boron concentration also need to increase to control the increased initial excess reactivity. The disadvantage of a higher critical boron concentration is that the MTC is less negative or even slightly positive, which can impair safety in the event of an Anticipated Transient Without Scram (ATWS). The second requirement is low boron concentration operation. For low-boron operation, the amount of BA needs to increase and it will cause the disadvantage of shorter cycle length due to the increased residual penalty and the reduced amount of uranium loading. In addition to that, it becomes harder to control the power peaking during operation with a higher amount of BA in the core.

Most LWRs use BAs for two major reasons: to control excess reactivity and to flatten power distribution. There are three types of BAs commonly used at present. Gadolinium oxide (Gd_2O_3) has been used in most PWRs. Gadolinium has a high absorption cross section, so the efficiency of Gd_2O_3 is high. However, since Gd_2O_3 is used in a mixture with UO_2, higher BA content reduces the amount of fissile isotopes in the FA. Also, the ^{235}U enrichment in the fuel with Gd_2O_3 should be lower than 2 w/o because of the low heat conductivity of UO_2–Gd_2O_3. These two facts can decrease the reactor cycle length. After the burnout of the gadolinium, there still remains a residual reactivity hold-down effect by the even mass number daughter isotopes of ^{155}Gd and ^{157}Gd (Cudrnak and Necas, 2011). The pin peak control also becomes more difficult as the number of Gd_2O_3 rods increases. The Integral Fuel Burnable Absorber (IFBA) developed by Westinghouse (WH) has a thin coating of ZrB_2 on the perimeter of the fuel pellets. IFBAs can be loaded within a FA in a variety of patterns with 8, 16, 64, or 104 IFBAs. The advantages of IFBAs are the reduction of the peak pin power in the FA and the minimum amount of replacement of fuel materials with BA, much smaller than Gd_2O_3. IFBA can be loaded in such a way that over 99% of the absorber materials are burned in the first 120 days of operation, but this early burnout is not a desirable feature for long cycle operation. There are some additional disadvantages of IFBAs. The first one is the production of helium from the reaction between ^{10}B and neutrons. The helium gas increases the internal pressure of the fuel rods. The second one is that the spatial self-shielding effect is low due to the fact that BAs are distributed over fuel rods in FAs. The Wet Annular Burnable Absorber (WABA)

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Table 1
Core parameters vs. fuel cycle length.[a]

Cycle length (month)	12	18	24
Number of feed FA	One-batch 60	Two-batch 64/28	Two-batch 104/44
Enrichment (^{235}U w/o)	4.160	4.545/4.940	4.545/4.950
Number of IFBAs	2752	9664	12,240
Number of WABAs	0	0	1728
Boron concentration at HZP (ppm)	1245	1957	2132
MTC (pcm/°F)	+2.5	+4.4	+4.5

[a] Reference 'Ozer and Edsinger (2001)'.

was developed by Westinghouse and is used for reactivity control of a MOX assembly (O'Leary and Pitts, 2001). Al_2O_3–B_4C annular pellets in Zircaloy are placed in a central flow-through water region (Hofmann et al., 1989). The advantage of WABA is high efficiency but the disadvantages are the flow area reduction due to its replacement of water in guide tubes and its inability to be installed at the control rod positions.

In this paper, a new concept of BA will be presented for advanced PWRs: a UO_2–$^{157}Gd_2O_3$ rod coated with a thin layer of ^{167}Er. The new BA has three major differences from the existing UO_2–Gd_2O_3. First, enriched ^{157}Gd is used to reduce the amount of Gd_2O_3 in the UO_2–Gd_2O_3 while maintaining the neutron absorption capability. Second, the fuel pellets are coated with a $ZrEr_2$ layer, so it is useful to reduce the amount of UO_2 displaced by the BA materials and to load more BAs in the FA. The last is the usage of enriched ^{167}Er. This helps to reduce the residual penalty of the BA and to extend the cycle length. This paper will demonstrate the advantages of the new BA rod in FAs and an equilibrium core. Various lattice codes have been developed for reactor core simulation (Choi et al., 2015; HELIOS Program, 2005; Park et al., 2014; CASMO-4E, 2009). In this paper, the assembly and core design calculations are performed by CASMO-4E/SIMULATE-3 with the ENDF/B-VI library (CASMO-4E, 2009; CMS-LINK User's Manual, 2009; SIMULATE-3, 2009).

2. New hybrid burnable absorber

2.1. Design of new BA

The requirements for a high performance BA for advanced PWRs are demonstrated in Fig. 1: (1) a suitable amount of excess reactivity needs to be provided at BOC, (2) a long cycle operation should be achievable, (3) the BA's burning rates should be maintained as flat as possible, and (4) the EOC residual absorber penalty should be minimized. Considering the above four requirements, two single isotopes are selected for the new design of a hybrid BA. Since natural element BA materials will leave their daughter isotopes after burning, a residual poisoning effect remains until EOC (Renier and Grossbeck, 2001). If the BA contains a single isotope, then the EOC residual reactivity penalty decreases significantly due to the low absorption cross section of the daughter isotopes (Renier and Grossbeck, 2001). A single isotope can be produced by laser isotope separation. ^{157}Gd and ^{167}Er are selected for the new hybrid BA. ^{167}Er can burn constantly for 4 years so it fits well with a long cycle operation (Renier and Grossbeck, 2001).

A new BA named R-BA is shown in Figs. 2 and 3. The BA material is $ZrEr_2$, which uses only the ^{167}Er isotope. The $ZrEr_2$ ring surrounds

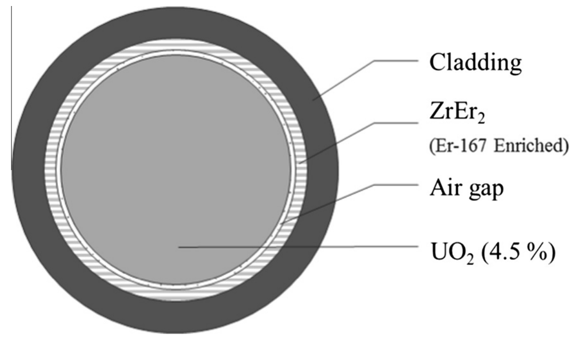

Fig. 2. Cross sectional view of enrichment zoning rod with R-BA.

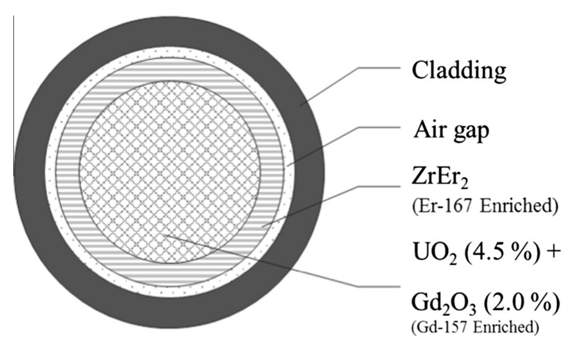

Fig. 3. Cross sectional view of Gd rod with R-BA.

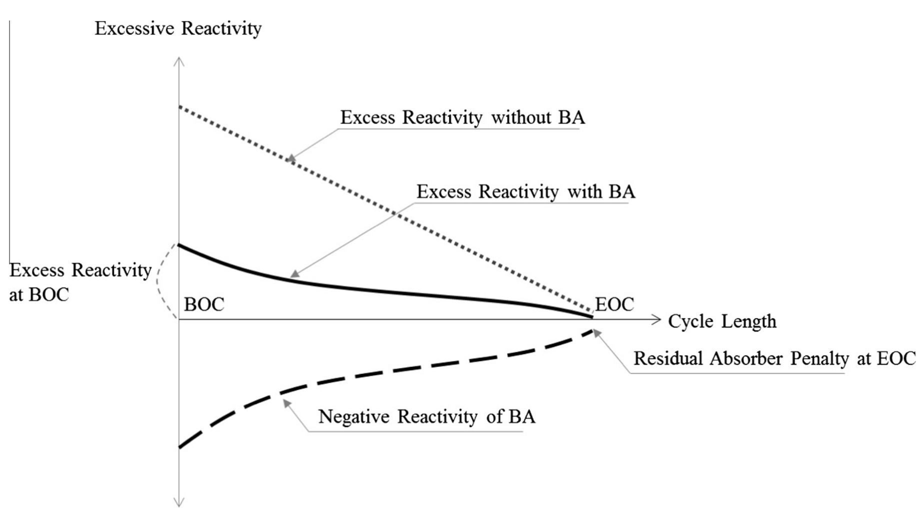

Fig. 1. Ideal BA design requirements.