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Burnable Absorber-Filled Annular UO_2 Fuels for PWR

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1. Introduction

Annular UO_2 fuel offers a number of significant advantageous as a candidate fuel for the modern PWR. Not only does annular fuel clearly require less uranium (U) inventory per pellet, it also has lower centerline temperature than the standard solid fuel, effectively improving its operating safety margin [1-2]. Its central annulus hole also provides an additional plenum for the fission gas release [3]. In fact, annular UO_2 fuels have successfully been used in commercial Russian's nuclear reactors for decades [4]. It was upon this notion that a study was recently performed to re-investigate neutronic characteristics of the annular fuel in a rod-cell lattice [5]. The said study also proposed an innovative integral burnable absorber (BA) concept by loading of a porous BA rod inside central hole of the annular fuel. This current work aims to extend the said investigation by characterizing neutronic performances of the BA-filled annular fuels in standard PWR 17x17 and 16x16 fuel assembly lattices. Preliminary results suggested promising potentials of the novel BA concept in managing the assembly lattice reactivity and power peaking. All calculations were performed using the Monte Carlo Serpent code [6] with ENDF/B7.0 library.

2. The BA-filled Annular Fuels

Figure 1 depicts design concept of the BA-filled annular fuel, which is a just standard UO_2 pellet but with a 1.0 mm radius central hole. It should be noted that the 1.0 mm radius central hole corresponds to 6% saving of U inventory from standard solid pellet [5]. The annulus hole is filled with heterogeneous layers of silicon carbide (SiC) ring and gadolinia (Gd_2O_3) rod. SiC is chosen for its high thermal and mechanical strength while Gd_2O_3 is selected for its very high thermal absorption and comparable melting point (2,420˚C) to UO_2 (2,865˚C). Gd_2O_3 can be replaced with other BA compounds per design specifications. Loading amount of the BA strongly dictates its neutronic performance, e.g. initial reactivity suppression and burnup-dependent depletion. One must note the BA self-shielding is rather optimized due to its circular rod shape. As such, depletion of the BA, especially of very black thermal poison such as gadolinium, is expected to be gradual and stays relatively flat during low burnup (<10 MWd/kgU).

The BA-filled annular fuels are envisioned to be uniformly loaded in standard PWR fuel assembly lattices, as illustrated in Figures 2.

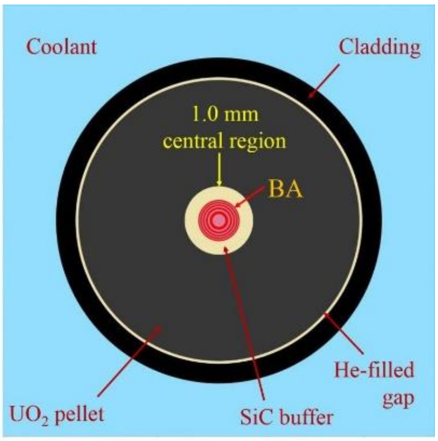

Fig. 1. Design concept of the BA-filled annular fuel.

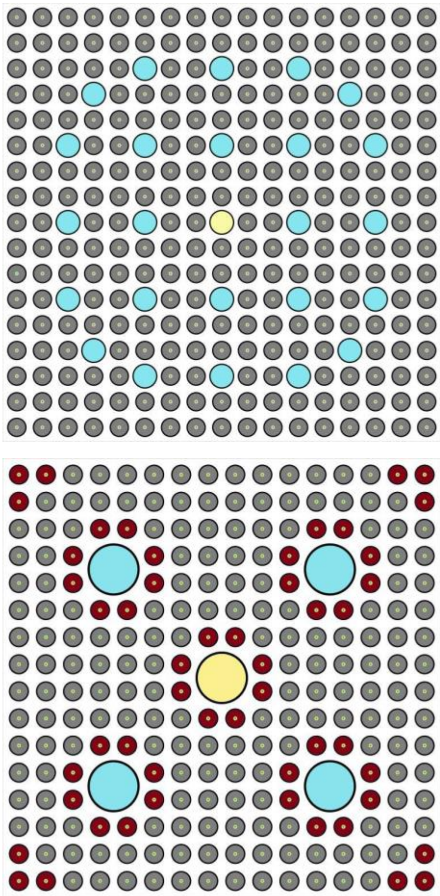

Fig. 2. BA-filled annular fuels in 17x17 (top) and 16x16 (bottom) assembly lattices. Note the 52 pins of lower-enriched UO_2 rods in the 16x16 configuration.

3. Benchmarking of the BA-filled Annular Fuels

Main objective of this research is to evaluate neutronic characteristics of the BA-filled annular fuels against commercial BA designs in standard 17x17 and 16x16 fuel assembly lattices. All Monte Carlo depletion calculations were performed with 120,000 histories per cycle, for 500 active and 100 inactive cycles, resulting in standard deviations of the lattice infinite neutron multiplication factors less than 9 pcm.

3.1 BA-filled Annular Fuels in 17x17 Assembly Lattices

The 17x17 fuel assembly lattice modeled in this work (Figure 2) is based on Westinghouse's AP1000 design [7]. The lattice contains 4.95-w/o UO_2 fuel rods of 95%TD (theoretical density) at 800K, cladding at 625K, and coolant without soluble boron at 600K. Depletion calculations were performed at 35.0 and 37.3 W/g specific power for 1,530 EFPDs (effective full power day) which correspond to 64.9 and 69.0 MWd/kgU burnup for solid and annular fuels, respectively.

The commercial BA design chosen as benchmark is 112 IFBA-rodded configuration used in AP1000 first core [7]. Two different loadings of Gd_2O_3 were simulated in this work. One (0.251 mm radius Gd_2O_3 rod) was determined such that its initial reactivity suppression matches with that of the benchmark. Another (0.4 mm radius Gd_2O_3 rod) was chosen so as to obtain initial reactivity suppression similar to reactivity of non-poisonous solid lattice at 490 EFPDs, i.e. EOC of cycle 1. The latter loading is potentially advantageous for a soluble boron-free (SBF) operation.

Figure 3 shows reactivity depletion of the simulated lattices with burnup. It is clear that reactivity of the two non-poisonous lattices (solid and annular fuels) are quite similar up to 400 EFPDs. Beyond that, the reactivity diverge gradually to 2,842 pcm differential at 1,410 EFPDs. Meanwhile, the two different loadings of BA-filled annular fuels show similar upswing after about 200 days of relatively flat depletion. This pattern of flat and quick reactivity upswing during low burnup is as expected due to the optimal BA self-shielding in the annular fuels.

Figure 4 shows evolution of the lattice power peaking factors with burnup. All lattices display reasonable power distribution, with peaking factors <1.07. Pin power maps of a representative BA-filled annular fuel configuration at different burnups are shown in Figure 5. It is clear that lattice hotspots stay around middle of the lattice throughout irradiation due to presence of water (moderator) in the guide thimbles. The lattice peaking factors can therefore be effectively managed via U enrichment-zoning of the corner pins.

Table I summarizes neutronic characteristics of the simulated assembly lattices. Fuel temperature coefficient (FTC) clearly becomes more negative with increasing BA loading. One also notes that rod worth of the annular fuel-loaded assemblies are noticeably higher than those of the solid fuel-loaded assemblies.

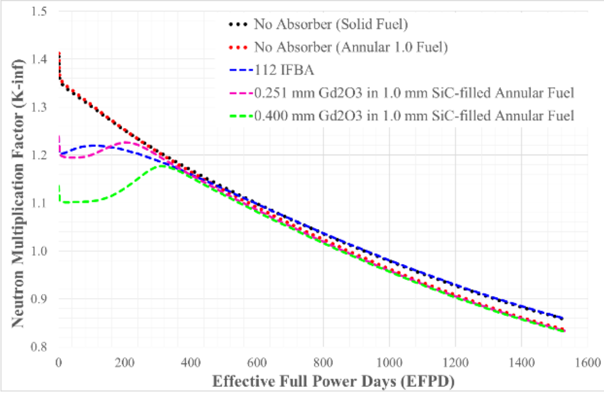

Fig. 3. Reactivity depletion of the simulated 17x17 fuel assembly lattices against burnup.

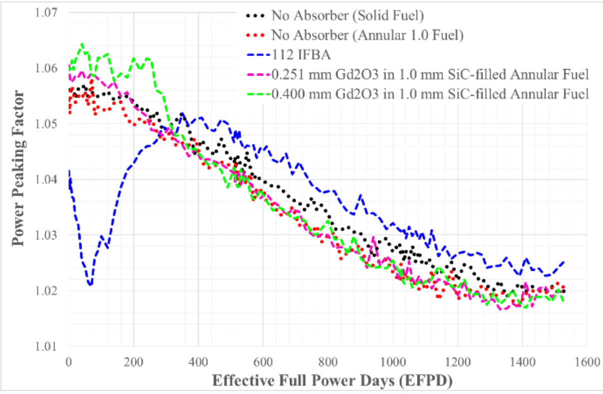

Fig. 4. Evolution of power peaking factors with burnup.

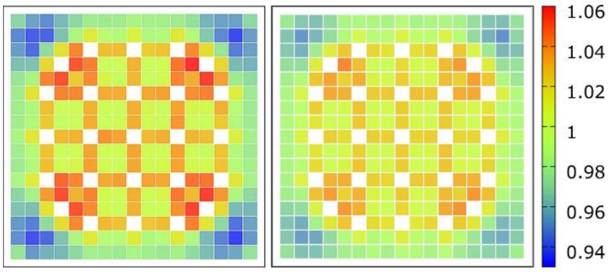

Fig. 5. Pin power maps of the representative BA-filled annular fuel lattices at 0 (left) and 490 EFPDs (right).

Table I. Neutronic Characteristics of the Different 17x17 Fuel Assembly Lattices

Fuel assembly lattices	Reactivity penalty at 1,410 EFPD (pcm)	Power peaking factor at BOC	Rod worth at BOC (pcm)	FTC at BOC (pcm/K)
No absorber (solid fuels)	0	1.057	32,363	-1.980
112 IFBA rods	231	1.052	31,588	-2.348
No absorber (annular 1.0 fuels)	-2,842*	1.058	33,489	-1.948
0.251 mm Gd_2O_3 (in SiC-filled in annular 1.0 fuels)	-335	1.060	34,115	-2.194
0.400 mm Gd_2O_3 (in SiC-filled in annular 1.0 fuels)	-591	1.064	34,662	-2.641

* reactivity differential from non-poisonous solid fuels

3.2 BA-filled Annular Fuels in 16x16 Assembly Lattices

The 16x16 fuel assembly lattice modeled in this work (Figure 2) is based on Korea's OPR1000 design [8]. The lattice contains 184 5.0-w/o and 52 4.50-w/o UO_2 fuel rods of 95%TD at 800K, cladding at 625K, and coolant without soluble boron at 600K. Depletion calculations were performed at 32.2 and 34.3 W/g specific power for 1,530 EFPDs which correspond to 56.0 and 59.5 MWd/kgU total burnup for the solid and annular fuels, respectively.

The commercial BA design chosen as benchmark is 12 gadolinia-bearing fuel (GBF) lattice configuration used in a number of different OPR1000 cores [8]. Two different loadings of Gd_2O_3 were simulated in this work; the first (0.260 mm radius Gd_2O_3 rod) was determined such that its initial reactivity suppression matches with that of the benchmark, and the second (0.368 mm radius Gd_2O_3 rod) was designed so as to potentially enable the SBF operation (i.e. its BOC reactivity suppression is similar to that of non-poisonous lattice at EOC cycle 1).

Figure 6 shows burnup-dependent reactivity of the simulated assembly lattices. Similar patterns to those of the 17x17 configurations are observed; i.e. comparable reactivity management to benchmark and reasonable control for an SBF operation. Figure 7 meanwhile shows evolution of the assembly power peaking factors with burnup. All configurations, except for the 12-GBF benchmark, clearly display power peaking factors <1.09. Zoning of U-enrichment in corner pins would further help managing the assembly peaking factors. It can thus be reasonably concluded that the BA-filled annular fuels can manage the assembly lattice reactivity and power distribution quite well.

Table II summarizes neutronic characteristics of the simulated 16x16 fuel assembly lattices. Again, FTC becomes noticeably more negative with increasing BA loading and rod worth is enhanced with deployment of annular fuels in the lattice.

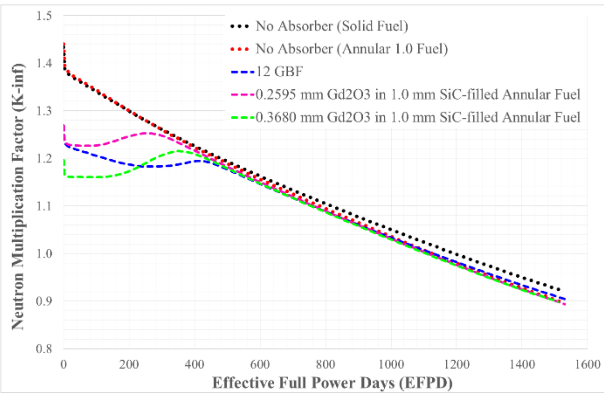

Fig. 6. Reactivity depletion of the different 17x17 assembly lattices (e.g. BA-filled annular and 12 GBF).

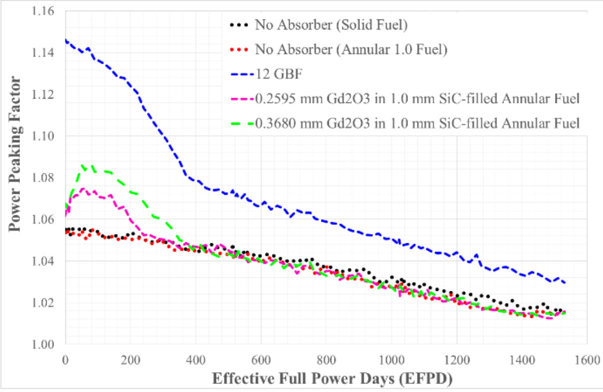

Fig. 7. Evolution of the assembly power peaking factors with burnup.

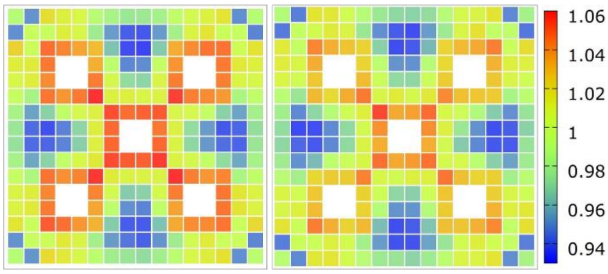

Fig. 8. Pin power maps of the BA-filled annular fuel-loaded lattices at 0 (left) and 490 EFPDs (right).

Table II. Neutronic Characteristics of the Different 16x16 Fuel Assembly Lattices

Fuel assembly lattices	Reactivity penalty at 1,410 EFPD (pcm)	Power peaking factor at BOC	Rod worth at BOC (pcm)	FTC at BOC (pcm/K)
No absorber (solid fuels)	0	1.057	17,438	-1.848
12 GBF rods	-1,827	1.146	18,624	-2.147
No absorber (annular 1.0 fuels)	-2,545*	1.055	17,861	-1.814
0.260 mm Gd_2O_3 (in SiC-filled in annular 1.0 fuels)	-314	1.075	18,739	-2.009
0.368 mm Gd_2O_3 (in SiC-filled in annular 1.0 fuels)	-485	1.086	19,212	-2.097

* reactivity differential from no absorber solid fuels

4. Conclusions

This paper demonstrates neutronic feasibilities of the BA-filled annular fuels in standard PWR 17x17 and 16x16 fuel assembly lattices. One notes that the BA-filled annular fuel-loaded lattice display comparable neutronic characteristics to the benchmarked commercial BA designs, especially in terms of reactivity and peaking factor management. Future study must include discussions of thermal analysis, economic viability and fabrication-process of the BA-filled annular UO_2 fuels.

ACKNOWLEDGMENT

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