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Optimization of Centrally Shielded Burnable Absorbers in Soluble-Boron-Free SMR Design

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1. Introduction

As one of the generation IV reactors, inherent safety and reliability are highly required in small modular reactors (SMRs). In particular, an increased level of autonomous operation, decrease of denpendence active control systems and enhanced capacity of power manipulating are highly demanded. Recent studies show that the use of soluble boron for reactivity control during the cycle is improper to meet these design targets [1,2]. On the other hand, it is illustrated that a soluble boron free (SBF) coolant system is advantageous for a fully-passive load-following operation in PWRs [3,4]. Besides, the SBF system is neutronically feasible for a cold reactor start-up in a water-cooled SMRs [5]. However, the SBF PWR has not been commercially established since it was first introduced in 1986 [6]. This is mainly due to shortage of burnable absorber (BA) designs that can dramatically suppress the reactivity swing throughout the cycle and consequently minimize the dependency on regulating control systems without reducing the reactor performances.

In order to remove soluble boron completely, a conceptually innovative BA design, centrally-shielded burnable absorber (CSBA), was proposed [7]. Basically, CSBA is a typical UO_2 pellet loaded with lumped BA in its centerline. The unique characteristic of the CSBA concept is that it can offer highly neutronic flexibility. The geometric aspect ratio of CSBA balls and their number per pellet dictates their spatial self-shielding effect. Therefore, an optimum depletion pattern with acceptable maximum reactivity swing can be achieved. Regarding integral BA, the fabrication feasibility is essential for successful implementation in practical applications. Experimental demonstration of fabrication process of CSBA loaded in the UO_2 fuel pellet is documented in a separate study [8].

This paper is dedicated to demonstrate the on-going effort for optimizing the CSBA design in the 3-D SBF SMR core for optimal operational conditions, for instance, an optimum reactivity swing less than 1000 pcm and greater than 500 pcm. This will significantly reduce the use of regulating control rods, with a reasonable operational margin. The numerical results show that with proper design of CSBA, the reactivity swing can be reduced significantly with an acceptable average-core burnup and relatively flat radial power distribution throughout the cycle. Therefore, the SBF can be achievable. To verify the neutronic feasibility of CSBA design, Monte Carlo Serpent 2 [9] code was used with ENDF/B-7.1 library. The number of histories is 500,00 per cycle with 100 inactive and 1000 active cycles, resulting in 10 pcm uncertainty of multiplication factor.

2. The CSBA concept and Lattice Analysis

Since a black BA such as gadolinia is used in a thermal reactor, it is important to enhance self-shielding of BA to reduce its burning rate to follow the slow fuel burning rate. In CSBA concept, the self-shielding effect of BA can be increased significantly since it is loaded into central region of the fuel pellet utilizing spatial self-shielding of fuel. In details, to offer highest self-shielding effect the single spherical BA is used in CSBA design, as shown in Fig. 1, since the sphere shape minimizes the exposed area. On the other hand, the self-shielding of BA can be easily manipulated by adjusting the number of BAs, from 1 ball to 3 balls. The self-shielding is also affected by geometric aspect ratio of the CSBA which depends on effective CSBA ball radius. With the same amount of BA, larger number of balls will decrease the self-shielding and subsequently accelerate the depletion rate of BA.

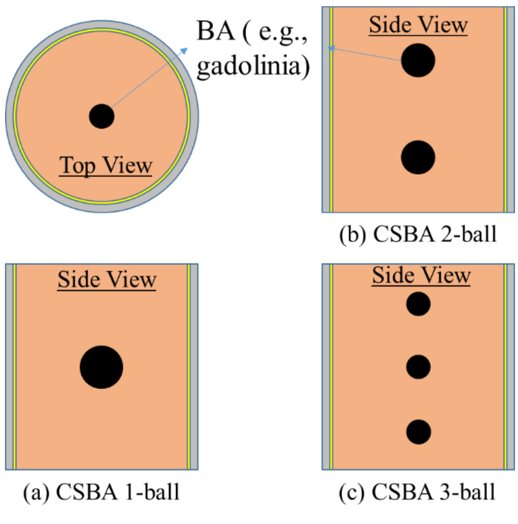

Fig. 1: Design configuration of CSBA fuels

As the BA is loaded into the fuel regions, CSBA is clearly classified as an integral BA type. One of the important advantages of the current CSBA design is that it remains inside the fuel pellet even if it melts. The proposed concept is also very favorable in view of the power peaking in the core, since it can be position-dependent loaded into all fuel pellets and power peaking factor should be rather small.

Fig. 2 and 3 depict the CSBA-loaded lattice analyses. The 17x17 PWR assembly was simulated with power density of 25.99 W/gU, which is the average power density used in SMR in the next section. The number of balls and their radii are varied to demonstrate the neutronics feasibility of the CSBA designs. It can be seen that the excess reactivity suppression and reactivity upswing are increased as the number of balls and ball radius increase. This is due to the larger amount of BA loaded and decreased self-shielding effect. It can be concluded that single-ball CSBA with relatively large radius should load in to high power regions, while others should be placed in lower power regions with small ball radius.

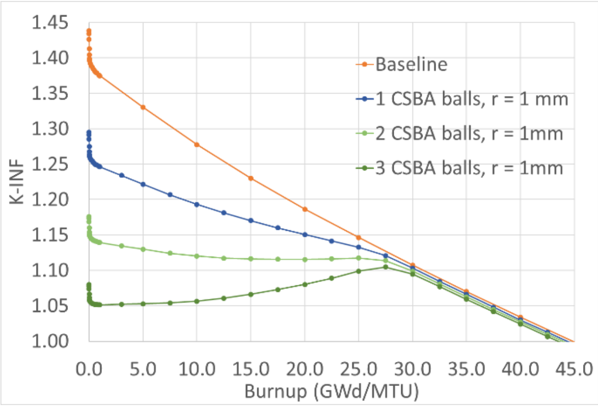

Fig. 2. Lattice analysis with various number of ball

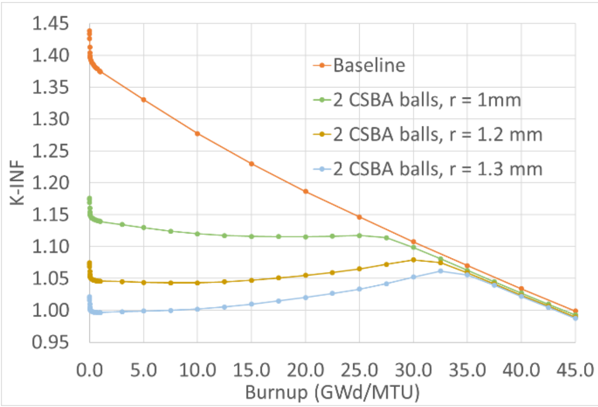

Fig. 3. Lattice analysis with various ball radii

3. SBF SMR core with CSBA

To investigate the practical neutronic feasibility of the CSBA concept, a 450 MWth SMR, with a single batch fuel management, was considered. The SMR core is the Autonomous Transportable On-demand Reactor Module core (ATOM). Table I shows major design parameters of the SMR core, while its radial and axial layouts are depicted in Figs. 4 and 5, respectively. There are 69 17x17 fuel assemblies and each fuel assembly consists of 264 fuel rods, 24 guide thimbles and a central in-core instrumentation tube. The maximum allowable enrichment of the fuel rods is 4.95-w/o with 95.5% theoretical density of the UO_2 pellet. The average-core power density is 25.99 W/gU, which is about 70% of the typical PWR one, with the aim of enhancing the reactor safety and operating thermal margin. The core equivalent diameter is around 201.6 cm and its active height is 200 cm, leading to a quite optimal height-to-diameter ratio of about 0.993.

The stainless steel assemblies are used as core reflector, instead of the typical water-baffle configuration, to enhance the neutron economy. Also, in the top and bottom core 5 cm axial fuel blankets are placed in the forms of 2.0 w/o UO_2 fuels to reduce axial neutron leakage. In addition, the core axial power peaking factor can be lowered by adapting 5 cm CSBA cutback layers.

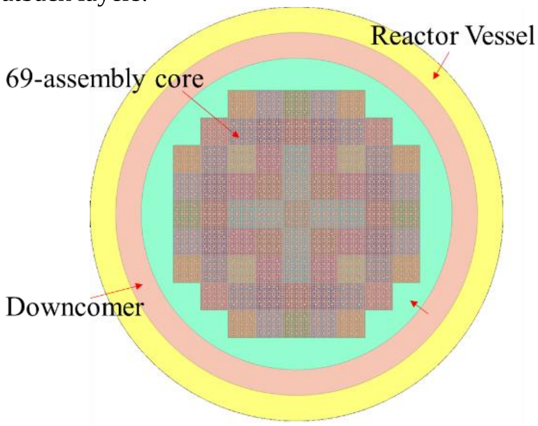

Fig. 4. SBF core radial layout

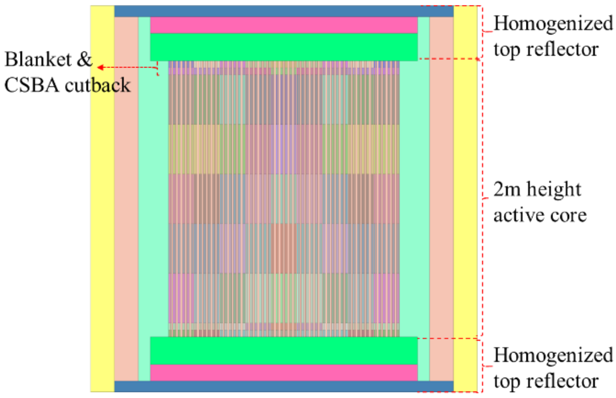

Fig. 5. SBF core axial layout

The single enrichment value of fuel, 4.95 w/o, is used throughout the whole core. The core is radially divided into 3 zones, in which various number and size of CSBA balls are also loaded to optimize the reactivity suppression and depletion rate, as shown in Fig. 6 and Table II. The single CSBA ball with relatively large radius is loaded into zone A to deaccelerate fuel depletion rates here, consequently reduce the power peaking factor. Less self-shielding designs, 2-ball and 3-ball CSBAs, are applied to zone B and C, respectively, as the powers at these zones are lower than at zone A in general.

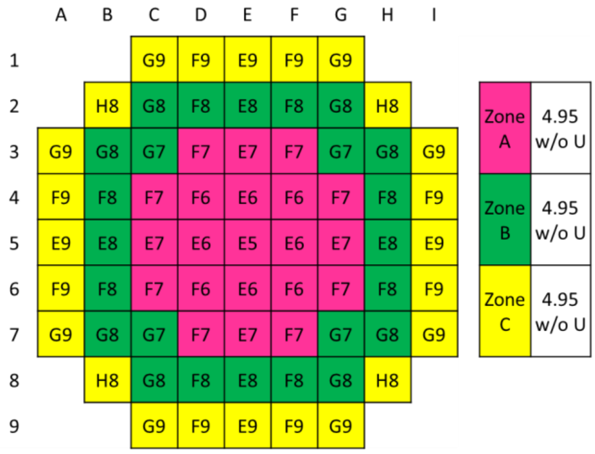

Fig. 6. Core fuel enrichment and CSBA loading pattern

Table I: Core major technical parameters

Parameters	Target Value	Unit
Thermal power	450	MWth
Active core height	200	cm
Equivalent diameter	201.6	cm
Height-to-diameter ratio	0.993	
Power density	25.99	W/gU
Cycle length	> 48	month
Fuel loading	Single-batch	
FA type	17 x 17	
Number of FAs	69	
Fuel materials	UO_2	
Fuel enrichment (max)	4.95	w/o

As shown in Fig. 7 the burn-up-dependent k_{eff} trend of the non-poisonous reference SBF core is against those of the preliminary CSBA-loaded ones. The cycle length of CSBA-loaded cases are around 31 GWd/tU or 46 months, which is slightly shorter than that of non-poisonous SBF core, about 33.5 GWd/tU or 50 months. The slightly shorter cycle length in the CSBA-loaded cores are mainly due to the reactivity penalty of the CSBA and partially due to a small fuel mass replaced by CSBA.

Table II. Zone-wise CSBA loading strategies

Case	Optimal CSBA designs		
	Zone A	Zone B	Zone C
1	1-ball r = 1.70 mm	2-ball r = 1.25 mm	3-ball r = 0.80 mm
2	1-ball r =1.172 mm	2-ball r = 1.25 mm	3-ball r = 0.78 mm

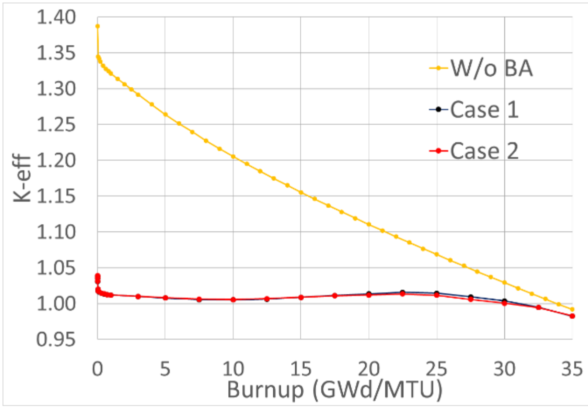

Fig. 7. Burn-up-dependent k-eff in CSBA-loaded ATOM core

The neutronic property of the two CSBA-loaded cases are tabulated in the Table III. In term of beginning-of-life (BOL) excess reactivity they are comparable, however a lower reactivity swing is accompanied with a shorter cycle length as a compensation. Case 2 is selected to be a reference since its upswing is rather small of 1326 pcm with acceptable burn up of 31 GWd/t. Figure 8 depicts normalized radial power profiles at 0, 15 and 30 GWd/tU burnup conditions for case 2. The core radial power distribution is almost uniform, from 0.80 to 1.2, at every burnup step. It should be noticed that associated uncertainties of the radial assembly peaking factors are less than 0.2%.

Table III: Neutronic property of CSBA-loaded cores

Case	Excess ρ at BOL (pcm)	Upswing ρ (pcm)	EOL penalty (pcm)
1	3707	1546	278
2	3748	1326	594

Fig. 9 shows the burnup-dependent axial power distribution. As expected, it is symmetric and the axially maximum power peaking factor of the core is slightly above 1.3 throughout the cycle. At BOL, the peaking factor is relatively small from the top to bottom fuel blankets due to the fresh CSBA loaded in the fuel pellets. At middle-of-cycle (MOL), CSBAs are largely depleted and the axial power profile returns to a usual cosine shape. At end of life (EOL), axial power distribution is quite flat as BA here is almost depleted. Associated uncertainties of the axial peaking factor is reasonably low, less than 0.5%.

	E	F	G	H	I	
6				0.808 0.826 0.799		
7			0.987 1.027 1.184	0.956 0.986 1.027	0.826 0.809 0.698	
8		0.972 0.919 1.223	1.004 0.984 1.195	1.093 1.113 1.097	1.126 1.063 0.810	
9	0.949 0.866 1.217	0.972 0.892 1.217	1.019 0.976 1.194	1.147 1.149 1.107	1.217 1.130 0.823	BOL (0 GWd/t) MOL (15 GWd/t) EOL (30 GWd/t)

Fig. 8. Normalized radial power profiles

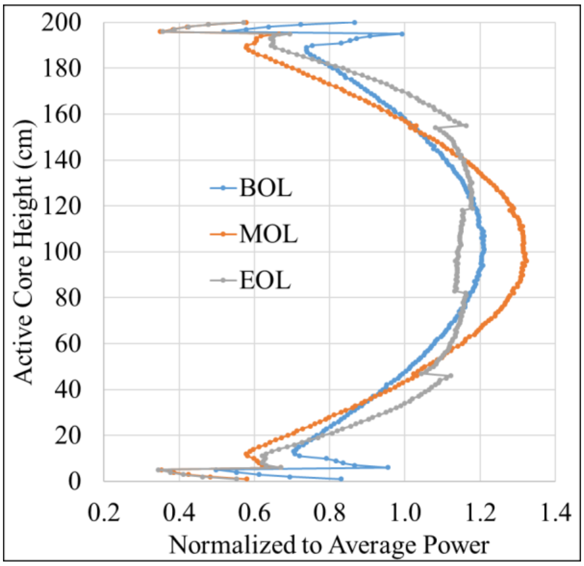

Fig. 9. Axial power profiles of the SBF core.

4. Conclusion

In this paper, the newly-proposed centrally-shielded burnable absorber (CSBA) concept is successfully applied to SBF SMR core. Various CSBA loading schemes are considered to minimize the excess reactivity and reactivity swing during the cycle and therefore minimize the required use of regulating control rods, while remaining the core performance. In the current optimal approaches, the burnup reactivity swing is about 1,300 pcm and the radial power peaking factor is clearly low, about 1.2. It is noted that the single enrichment is used in whole core, hence, investigation on fuel management can reduce further reactivity swing and power peaking factor. The results demonstrated in this work show the high potentials of CSBA for effectively controlling the depletion rate of gadolinia, and minimizing the reactivity during the cycle for a successful SBF operation. In terms of neutronics, it can be concluded that with implementation of CSBA technology, an SBF core is totally achievable. Further work is on-going for optimizing the ATOM core design for an optimal SBF operation.

ACKNOWLEDGMENTS

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