Transactions of the Korean Nuclear Society KNS Spring Meeting 2017. May 17-19. ICC Jeju

Soluble-Boron- Free SMR Design with Centrally Shielded Burnable Absorbers

Ahmed Amin E. Abdelhameed, Chihyung Kim and Yonghee Kim*
Korea Advanced Institute of Science and Technology,
291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Korea
**Corresponding author: yongheekim@kaist.ac.kr*

1. Introduction

For developing next-generation reactors with increased level of safety and autonomous operation, an increased level of neutronic flexibility per operational sophistications is highly demanded. Although burnable absorbers (BA) have been under developing throughout the years, innovations in BA technologies are not yet fulfilling the highly required advancement in pressurized water reactors (PWRs). Upon this motivation, an innovative BA design named "Centrally-shielded burnable absorber" (CSBA) is proposed. In this work we demonstrate CSBA design concept and its advantages; especially in offering higher level of neutonic flexibility.

In addition, we show its application in a 3-D small modular reactor core. BA materials are deployed as either integral or discrete designs in modern PWRs [1]. In the integral design, BA such as gadolinia and erbia is directly admixed with UO_2 fuel. In spite of its relatively simple fabrication, admixing BA to ceramic fuel adversely affects UO_2 fuel thermal-mechanical properties, such as degraded thermal conductivity and reduced melting point. These adverse effects, when compounded with typical restriction of <2.5 w/o uranium enrichment in the BA-bearing pellet, severely limits number of the integral BA fuel pin in a PWR core [2].

In discrete design loads BA materials into non-fuel element of the fuel assembly. One such example is the wet annular burnable absorber rod, which occupies water hole of a standard guide thimble and thus denies insertion of control rod. Another variant is the solid BA rod installed in place of a fuel rod. This design effectively displaces fissile content originally available in the fuel assembly. In a nutshell, while state-of-the-art PWR BAs reliably help to control the core reactivity, each comes with characteristic drawbacks. It is upon these observations that new and innovative BA designs are necessary to meet the demands of modern PWR cores. Such an innovative BA *discrete* concept had previously been developed. The said concept, named "burnable absorber-integrated guide thimble" (BigT) [2].

2. CSBA Design Concept

To complement the *discrete* BigT design, an innovative *integral* BA concept named "centrally-shielded burnable absorber" (CSBA) is proposed in this research. CSBA is basically a typical UO_2 pellet with lumped gadolinia cores as shown in Figure 1. It takes advantage of sphere as the shape with the highest volume-to-surface area ratio. By encapsulating the thermally-black gadolinia as a spherical ball inside the fuel pellet, CSBA thus maximizes gadolinia's neutronic spatial self-shielding and thereby dampen its depletion rate in a thermal spectrum. To adjust gadolinia's self-shielding and its resulting burnup-dependent consumption rate, the gadolinia ball can be split into two or three balls. Note that the balls should be loaded symmetrically axial-wise, taking into account gadolinia balls in the neighboring pellet. The CSBA concept may also utilize mini-balls within a cylindrical UO_2 or ZrO_2 buffer layer in order to further reduce gadolinia's self-shielding. Experimental demonstration of the essential fabricability of the CSBA concept is documented in a separate research paper [3].

Table I lists material properties of the CSBA components. One notes that melting point of gadolinia is lower than urania; as such, it is possible that gadolinia may accidentally melt before urania in a non-accident scenario. Nonetheless, in these circumstances, it is assumed that the melted gadolinia can safely be contained within the pellet.

TABLE I. Material properties of CSBA components [3]

Parameters	Gd_2O_3	UO_2
Melting point (˚C)	2,340	2,860
Density at 25˚C (g/cm^3)	7.4	10.96
Thermal conductivity at 25˚C (W/m·K)	6.2	8
Coefficient of thermal expansion at 25˚C (K^{-1})	10.5	9.75
Thermal σ_a(barn)	^{155}Gd: 61,100 ^{157}Gd: 259,000	^{235}U: 681 ^{238}U: 3

It should also be noted that density of the gadolinia increases rapidly beyond 1250˚C as its crystal structure changes from cubic to monoclinic at that temperature. Meanwhile, thermal conductivity of UO_2 decreases asymptotically with temperatures, from 8 to 5~3.8 W/mK when its temperature goes from 25˚C to 325~625˚C. Linear coefficients of thermal expansion for the two oxides can be reasonably be assumed constant throughout the reactor operation. Nonetheless, the slight mismatch of thermal expansions between gadolinia and urania is of a considerable concern. This concern can practically be assuaged by integrating a buffer layer which separates gadolinia from urania so as to accommodate their different thermal expansion rates.

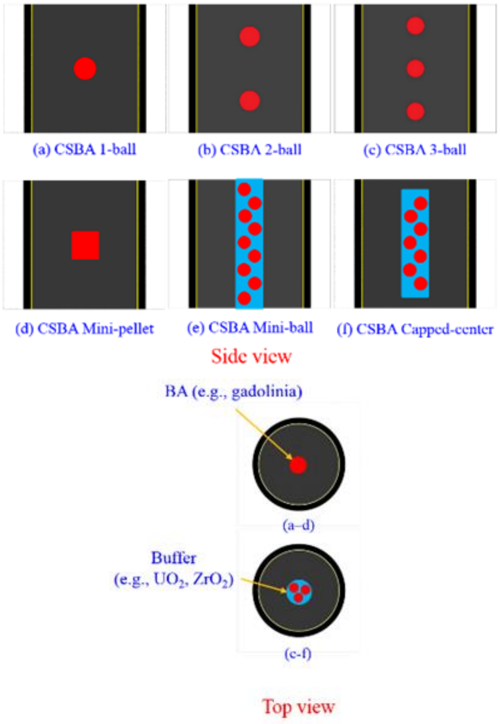

Fig. 1 Design concepts of CSBA fuels

3. CSBA in 3-D PWR Core

This study was conducted to demonstrate how well neutronic characteristics of the CSBA design is transferred from fuel assembly level to 3-D PWR core application. For this study, KAIST's own ATOM (Autonomous Transportable On-demand reactor Module) is chosen as the model PWR core configuration. Specifications of the ATOM core are tabulated in Table II. The reactor is designed to produce 450 MWth core power for a four-year cycle on a single-batch fuel management. The core equivalent diameter is about 201.6 cm and its active core height is 200 cm, resulting in an almost optimal height-to-diameter (H/D) ratio of about 0.993. The core power density is 70.5 kW/l, which is about 70% of a typical large PWR. For a successful soluble-boron-free (SBF) operation, the ATOM core reactivity swing should be minimized.

The ATOM core is consisted of 69 fuel assemblies as illustrated in Figures 2 and 4. Each fuel assembly is a 17x17 array of 264 fuel rods, 24 guide thimbles and a central in-core instrumentation tube. Enrichment of the fuel rods are limited to 4.95 w/o UO2 of 95.5%TD pellets. Obviously, fuel enrichment zoning is necessary for the successful SBF operation. In this study, however, each fuel pellet is loaded with uniform UO2 enrichment (4.95 w/o) and CSBA 2-ball design shown in Fig. 2.

Note that the ATOM core is quite compact; i.e. it is almost half the size of a large commercial PWR. As such, relatively huge neutron leakage is expected from this small reactor core. In order to improve its neutron economy, the ATOM core thus utilizes steel reflector assembly instead of typical baffle-reflector configuration. This helps to reduce the core radial neutron leakage quite significantly. To further minimize the neutron leakage, the core also uses 5 cm top and bottom axial fuel blankets in the forms of 2.0 w/o UO2 fuels. Additionally, 5 cm CSBA cutback layers are also used to further control the core axial power peaking.

The 3-D Serpent core was modeled with octant-symmetrical depletion sub-divisions of 9 axial depletion meshes that include 4 stacks of fuel blankets and CSBA cutbacks. Top and bottom of the core were each capped with homogenized reflectors. In this study, it is assumed that the fuel and coolant temperatures are constant at 750K and 575K, respectively, throughout the depletion calculations. As such, multi-physics coupling was not considered in this work partly due to the current computational capability limitation of Monte Carlo Serpent code. To further simplify this study, top and bottom reflectors are assumed identical so as to assure symmetrical axial power profiles. The Monte Carlo Serpent [4] model was simulated with 50,000 particles per cycle for 1,000 active and 500 inactive cycles, resulting in standard deviations of the effective neutron multiplication factors (k-eff) less than 15 pcm.

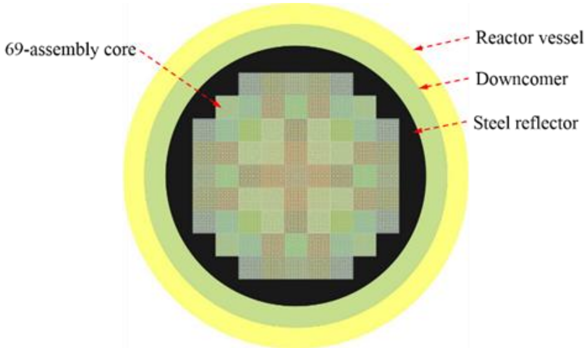

Fig. 2. The ATOM core radial layout.

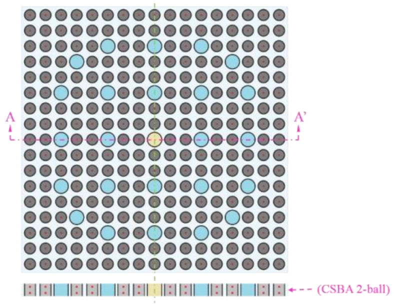

Fig. 3. The ATOM core radial layout.

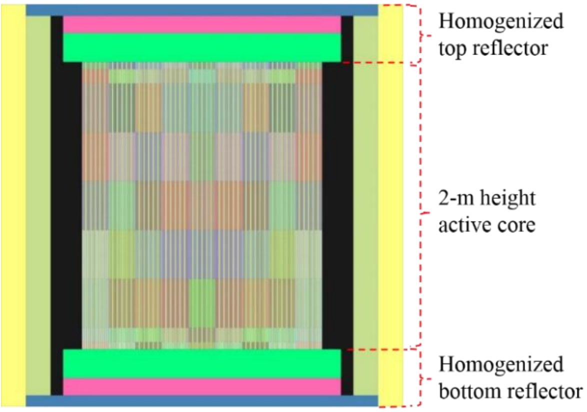

Fig. 4. The ATOM core axial layout

Figure 5 shows burnup-dependent reactivity depletion pattern of a representative ATOM fuel assembly loaded with CSBA 2-ball of radius 1.36 mm. Figure 6 meanwhile depicts burnup-dependent k-eff trends of non-poisonous ATOM core against those loaded with CSBA 2-ball designs of radii 1.0, 1.20 and 1.36 mm. X-axes of these plots are clearly on different scales; one assembly- and another core-level. In the infinite 3-D lattice depletion calculation, the assembly reactivity shows significant upswing near 20 MWd/kgU as well as noticeable penalty at 60 MWd/kgU due to the neutronic characteristics of CSBA designs.

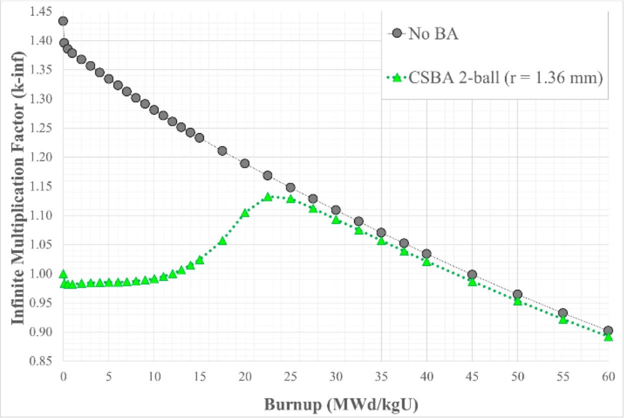

Fig. 5. Burnup-dependent k-inf of the CSBA-loaded ATOM fuel assembly.

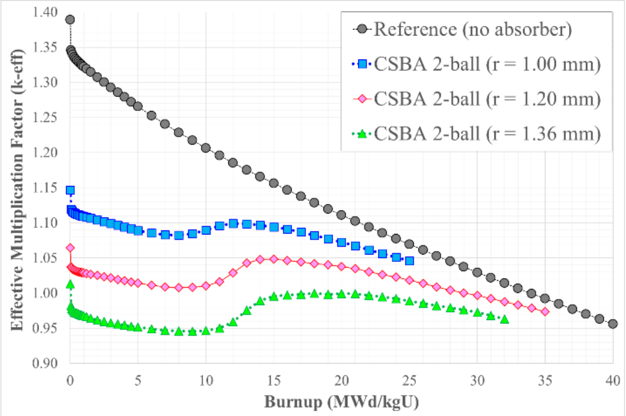

Fig. 6. Burnup-dependent k-eff of the CSBA-loaded 3-D ATOM cores.

This is nevertheless expected since the 3-D core calculations take into account neutron leakages. Furthermore, uneven power loading (axially and radially) of the location-dependent assemblies also affect consumption rates of gadolinia balls in the CSBA pellets. Incomplete BA consumption in the low-powered assemblies result in core residual reactivity penalty at EOL, shortening the core discharge burnup (33.5 MWd/kgU for non-poisonous core and 29.5 MWd/kgU for CSBA 2-ball of 1.20 mm radius). Higher discharge burnup can be available with smaller CSBA radius design, and vice versa. All these factors must thereby carefully be deliberated in any CSBA core application. Obviously, CSBA zoning is necessary for a practical core reactivity and power management.

TABLE II. Specifications of the ATOM Core

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	70.5	kW/l
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
Boron concentration	0	ppm

4. Conclusions

A novel innovative integral BA concept for PWR named "centrally-shielded burnable absorber" (CSBA) is conceptualized in this paper. Specifically, this paper demonstrates promising potentials of the CSBA concepts in a representative 17x17 fuel assembly and a 3-D SMR core application. The CSBA concepts are shown to perform reasonably well in comparison with commercial BA technologies, especially in terms of reactivity depletion and power distribution managements. Further studies to fully investigate practical applications of the CSBA concepts must be pursued. This is especially important as CSBA can also be applicable to other PWR designs, such as Korean's APR1400 and French's ERP reactors. In essence, CSBA can potentially be a new standard of the PWR BA technology.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korean Government (MSIP) (NRF-2016R1A5A1013919).

NOMENCLATURE

ATOM:	Autonomous Transportable On-demand reactor Module
BA:	Burnable Absorber
BigT:	Burnable absorber-Integrated Guide Thimble
CSBA:	Centrally-Shielded Burnable Absorber
EFPD:	Effective Full Power Day
IFBA:	Integral Fuel Burnable Absorber
PWR:	Pressurized Water Reactor
SBF:	Soluble-Boron-Free
SMR:	Small Modular Reactor
TD:	Theoretical Density

REFERENCES

1. J.R. SECKER and J.A. BROWN, "Westinghouse PWR Burnable Absorber Evolution and Usage," *Trans. Am. Nucl. Soc.* 2010 Nov; 103:733-734.
2. M.S. YAHYA, H. YU and Y. KIM, "Burnable absorber-Integrated Guide Thimble (BigT) – I: Design Concepts and Neutronic Characterization on the Fuel Assembly Benchmarks". *J. Nucl. Sci. Tech*. 2016 Jul; 53 7:1048-1060.
3. Q. MISTARIHI, M.S. YAHYA, Y. KIM and H.J. RYU, "Fabrication Process of Neutron Absorber Inserted Oxide Fuel Pellet", *12th Pacific Rim Conference on Ceramic and Glass Technology (PACRIM 12), including Glass & Optical Materials Division Meeting (GOMD 2017)*, Hawaii (USA), 21 – 26 May 2017.
4. J. LEPPÄNEN, M. PUSA, T. VIITANEN, V. VALTAVIRTA and T. KALTIAISENAHO, "The Serpent Monte Carlo Code: Status, Development and Applications in 2013," *Ann. Nucl. Energy*. 2015 Aug; 82:142-150.