Optimization of the Three-Batch ATOM Core Design Utilizing the Cylindrical CSBA-Loaded TOP Fuel Assembly

Xuan Ha Nguyen, Yunseok Jeong, and Yonghee Kim
Nuclear Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea
**Corresponding author: yongheekim@kaist.ac.kr*

1. Introduction

Small reactivity swing during the cycle in pressurized water reactors (PWRs) has been demonstrated to be the most important design target to achieve soluble-boron-free (SBF) operation [1] [2]. The SBF operation offers numerous advantages, such as fast reactivity control, less radioactive waste, improved inherent safety, and etc., [1]. In addition, the criticality of the core can be achieved with a weak control rod (CR) group, which minimizes peaking factor due to CR insertion. To obtain a small reactivity swing, burnable absorber (BA), which is the major reactivity control, should deplete gradually throughout of the cycle. Therefore, spatial self-shielding of the BA should be optimized appropriately by adjusting its surface area per unit volume.

Recently, an advanced 3-D BA design, so-called centrally-shielded BA (CSBA), has been developed for a PWR-type small modular reactor (SMR), autonomous transportable on-demand reactor module (ATOM) core [1]. The shape of CSBA and the number of CSBA per fuel pellet dictate the spatial self-shielding and its depletion rate. The CSBA was successful to manage the reactivity swing in single- and two-batch fuel managements (FMs), in which spherical CSBA was utilized as its exposed area is minimal for a given BA volume [1] [3]. However, the significant spatial self-shielding of CSBA ball is unfavorable for a three-batch FM as amount of the BA loading is rather limited due to less number of feed fuel assembly (FA). Therefore, cylindrical CSBA, a less shielded design, was proposed for the three-batch ATOM core [4] and enhanced-moderation FA, so-called truly-optimized PWR (TOP) lattice, are used to improve the neutron economy.

In this paper, the fuel shuffling scheme and radial CSBA loading pattern for the 3-batch ATOM core are optimized to achieve 1,000 pcm reactivity swing. In addition, a new axial BA zoning is introduced to mitigate the axial power oscillation while minimizing the radial peaking factor. Inherent safety parameters, fuel and moderator temperature coefficients are also evaluated. All of neutronic evaluations are performed by using the Monte Carlo Serpent 2 [5] with library ENDF/B-VII.1.

2. Three-Batch ATOM Core

2.1 Burnable Absorber Design

In PWRs, BA is commonly used to dwindle the excess reactivity. To reduce fabrication cost, the BA is often mixed into fuel or coated on the surface of the pellet [6]. The conventional 2-D BAs deplete rapidly as it exposes largely to neutron flux. Therefore, the major excess reactivity is mainly governed by soluble boron since the BA content should be limited. Meanwhile in the SBF operation, the excess reactivity is mainly compensated by the BA and the rest is controlled by a group of weak CRs. As such, the amount of BA loading is significant and must be concentrated in a small volume to minimize its burnup rate. Hence, 3-D BA design is advantageous as its surface area is minimized.

In the SBF ATOM core, spherical CSBA was used for the single- and two-batch FMs as it offers the strongest self-shielding effect and is also shielded by the fuel [1] [4]. Compared to spherical CSBA, the cylindrical CSBA is highly flexible in terms of the self-shielding effect since the spatial self-shielding can be easily manipulated by adjusting height-to-diameter (HTD) ratio. Moreover, less-shielded cylindrical CSBA can be also obtained by increasing the number of CSBA per fuel pellet. In this paper, two-cylinder CSBA design is used as shown in Fig. 1. The CSBAs are placed so that they uniformly distribute along the fuel rod. Gd2O3 is used as BA material as it is well-mature in PWR technology and most effective BA in controlling the excess reactivity.

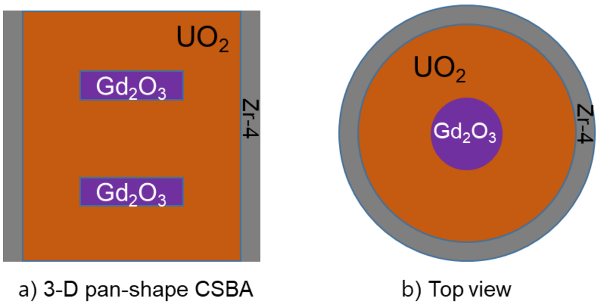


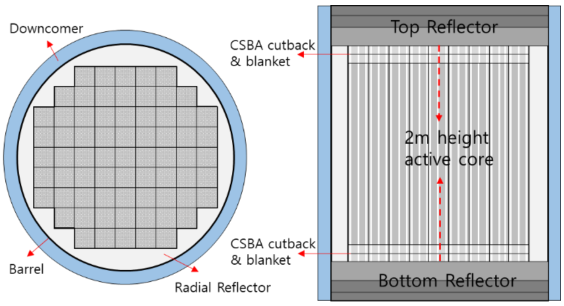
Fig. 1. 2-cylinder CSBA-loaded fuel pellet.

2.2 The Three-Batch Core Design and BA Loading

The design parameters and views of the ATOM core are shown in Table I and Fig. 2, respectively. The core has 69 17x17 TOP FAs and each FA comprises 264 CSBA-loaded rods and 25 guide thimbles. The TOP fuel radius is 0.38 cm with the hydrogen-to-uranium ratio of 5.0, while the gap and cladding thicknesses are the same [7]. The uranium enrichment is 4.95 w/o with 95.5 theoretical density. The core adopts 5 cm boundary regions with the enrichment of 2.0 w/o and 3.0 w/o UO_2 at the top and bottom, respectively. The thermal output is 450 MWth with a 3-batch fuel FM. The number of fresh is 23.

Table I: ATOM core design parameters

Parameters	Value
Thermal output	450 MWth
Fuel radius	0.38 cm
Pin pitch	1.26230 cm
Fuel materials, enrichment	UO_2, 4.95 w/o
Fuel management	3-batch
Active core height	200 cm
No. of fresh FA	23
BA design	Cylindrical CSBA
FA type, number of FA	TOP, 69
Inlet / outlet coolant Ts	295.7 / 323 ^{0}C
Radial reflector	SS-304
Reactivity swing	~ 1,000 pcm



a) Radial layout b) Axial layout

Fig. 2. The axial and radial views of the ATOM core

The core utilizes a scattered shuffling scheme as depicted in Fig. 3 and Table II. The feed FAs are largely placed in the inner region while the once-burnt FAs are resided in the periphery ones. Twice-burnt FAs are also placed in the inner positions for a flat radial power. The feed FAs are divided into three zones and each zone is loaded with a unique cylindrical CSBA design.

Table II: Three-batch fuel shuffling scheme

Fresh	One-burnt	Twice-burnt
E5, C5, B2,	F5, A3, D4	D5, D3, E2,
B8, E3, E7	D6, G1, C9,	B5, G4, C6,
H2, H8, G5,	F4, F6, I7,	H5, E8, F7,
A5, B4, B6	E1, A4, A6	E4, C2, C8,
C3, C7, D2,	C1, A7, D1,	F3, C4, B3,
D8, F2, F8	D9, F1, F9,	B7, H3, H7,
G3, G7, H4,	I3, G9, I4,	G6, D7, G2,
H6, I5	I6, E9,	G8, E6

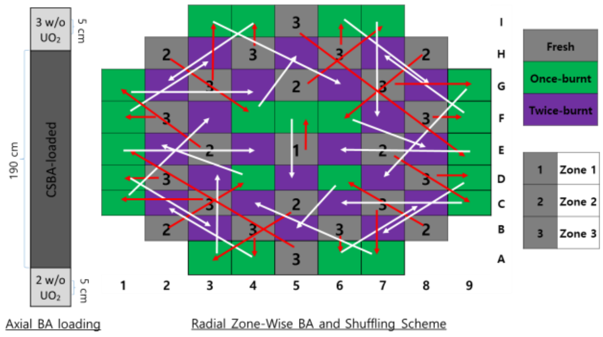


Fig. 3. BA loading pattern and fuel shuffling scheme

The BA loading pattern is shown in Table III. To reduce radial peaking, the biggest CSBA is loaded into the inner regions, zone 1 and 2, while the smallest ones are utilized in zone 3. Zones 1 and 3 has the same HTD ratio of 0.15, while the HTD of zone 2 is 0.20. In the axial direction, the BA of each zone is divided into six layers which has the same HTD ratio, but volume. This is to balance the axial power distribution due to higher coolant density at bottom of the core. In this study, coolant temperature is assumed to change linearly from the bottom to the top of the active core. In addition, the enrichment of fuel in zone 1 is reduced to 3.5 w/o to lower the power peaking in the center of the core.

Table III: CSBA loading strategy

Axial position	CSBA Volume (mm^3)		
	Zone 1	Zone 2	Zone 3
190-195 cm	3.0	3.0	3.0
160-190 cm	4.0	6.0	3.7
100-160 cm	5.0	6.4	4.5
40-100 cm	5.2	6.4	4.7
10-40 cm	4.2	6.4	4.1
5-10 cm	3.0	3.0	3.0

3. Numerical Results and Discussion

The Monte Carlo Serpent 2 [5] core is used in conjunction with ENDF/B-VII.1 to analyze the performance of the three-batch ATOM core. The number of active and inactive cycles are 200 and 100, respectively, with 100,000 histories per cycle. The standard deviation of the effective multiplication factor (k_{eff}) is less than 26 pcm while the standard deviation of the power is less than 0.6%. The effective temperature of the fuel is 900K and the average coolant temperature is 582.5K. Along the axial direction, the coolant temperature is linearly varying from the bottom to the top of the core for more practical simulation. Each CSBA is split into 10 equivolume depletion regions considering accurately the spatial self-shielding effect.

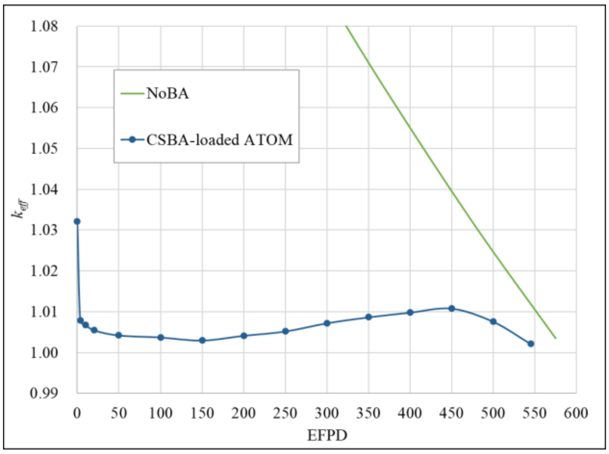


Fig. 4. The k_{eff} evolution of the equilibrium ATOM core

The neutronic performance of the three-batch ATOM core are described in both Fig. 4 and Table IV and compared to the nonpoisonous case. One can observe that the burnup reactivity swing (BRS) is about 1,069 pcm, which is close to the target value. Note that the reactivity swing is defined as the maximum excess reactivity under xenon equilibrium. The cycle length of the core is 545 effective full power day (EFPD), about 18.2 months, with an average discharge burnup of 49.24 GWd/tU.

Table IV: Neutronic performance of the ATOM core

Case	BRS (pcm)	Cycle length (EFPD)	Dis. Burnup (GWd/tU)
No BA	-	575	51.01
CSBA	1,069	545	49.24

		0.63 0.55 0.61	0.81 0.74 0.88	0.74 0.77 1.06	0.80 0.74 0.85	0.59 0.55 0.57		BOC MOC EOC
	0.55 0.53 0.56	0.80 0.74 0.80	1.03 1.11 1.48	0.97 0.92 1.07	1.03 1.13 1.42	0.81 0.74 0.78	0.54 0.52 0.56	
0.73 0.58 0.51	0.94 0.81 0.78	1.14 1.26 1.40	1.12 1.10 1.07	1.12 1.31 1.50	1.17 1.15 1.07	1.14 1.27 1.34	0.94 0.82 0.74	0.77 0.60 0.51
1.11 0.82 0.70	1.31 1.28 1.30	1.26 1.20 1.04	1.25 1.63 1.29	1.14 1.23 0.97	1.25 1.63 1.27	1.23 1.18 1.01	1.23 1.28 1.25	1.06 0.85 0.69
1.25 0.97 0.78	1.35 1.07 0.95	1.29 1.42 1.44	1.21 1.32 1.03	0.90 1.40 1.19	1.18 1.29 1.02	1.23 1.39 1.41	1.22 1.04 0.92	1.15 0.99 0.77
1.18 0.83 0.70	1.37 1.31 1.31	1.33 1.22 1.08	1.19 1.55 1.29	0.73 0.90 0.80	1.14 1.52 1.30	1.21 1.17 1.07	1.23 1.27 1.33	1.04 0.83 0.71
0.86 0.60 0.54	1.03 0.83 0.79	1.19 1.31 1.43	1.16 1.15 1.14	1.03 1.23 1.51	1.07 1.09 1.12	1.11 1.26 1.47	0.93 0.82 0.81	0.71 0.59 0.53
	0.57 0.54 0.59	0.81 0.76 0.83	1.05 1.17 1.55	1.01 0.99 1.17	1.03 1.16 1.56	0.83 0.77 0.85	0.54 0.54 0.60	
		0.59 0.59 0.65	0.81 0.79 0.94	0.76 0.83 1.15	0.83 0.80 0.94	0.67 0.60 0.65		

Fig. 5. Radial assembly-wise power profile.

The radial power distribution for the cylindrical CSBA-loaded ATOM is presented in Fig. 5. The radial peaking, about 1.63, is found at F4 and F6 FAs at middle of cycle (MOC). It is due to the asymmetry of the 3-batch FM core as the number of fresh FA is odd, 23 FAs. It is suggested that further optimization of the BA and possible enrichment zoning are needed to reduce the radial peaking factor.

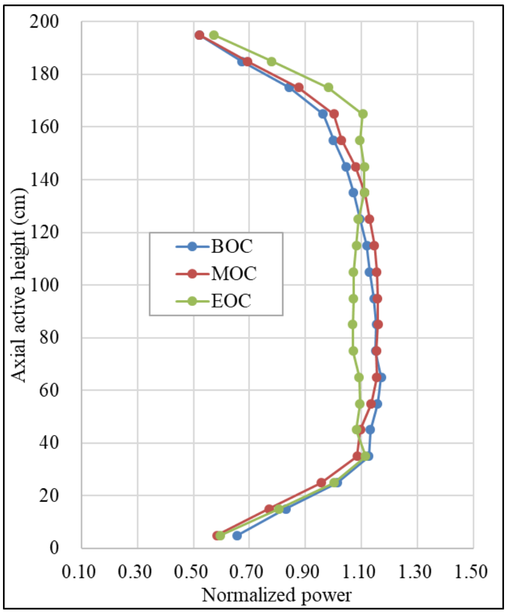


Fig. 6. Axial core-average power profile.

On the other hand, the axial core-average power profile is depicted in Fig. 6. It can be seen that the power distribution is slightly bottom-skewed at beginning of cycle (BOC), and then becomes cosine-shaped at MOC. A typical slightly saddle power profile is observed at the end of cycle (EOC). Thanks to the axial CSBA zoning, the axial power oscillation is eliminated from the reference [4]. Moreover, the axial peaking factor is really small, less than 1.20, at any condition.

	1	2	3	4	5	6	7	8	9
I									
H			48.56		48.98		48.85		
G		46.22		51.08		49.48		46.79	
F			51.00				50.40		
E		50.32		50.75		50.17		50.79	
D			49.39		52.50		50.45		
C		46.71		48.82		49.93		46.42	
B			49.10		47.58		48.32		
A									

Fig. 7. The discharge burnup distribution of the ATOM core

The discharge burnup of the ATOM core is shown in Fig. 7. One can see that the discharge burnup distribution is flat as the maximum value is about 52.50 GWd/tU and the minimum one is around 46.22 GWd/tU. D5 FA has the highest discharge burnup even though it is loaded with 3.5 w/o UO_2. It is because it is loaded in the center of the core. On the other hand, the average discharge burnup is about 49.24 GWd/tU which is very comparable to that of the big-size PWRs. It is indicated that the use of the TOP lattice is highly advantageous for the SMRs.

The inherent safety parameters, moderator temperature coefficient (MTC) and fuel temperature coefficient (FTC), are tabulated in Table V. These coefficients are evaluated at both BOC and EOC conditions assuming that they are linear functions of temperature. It can be observed that the FTC values are quite typical, -2.55 pcm/K at BOC and -2.53 pcm/K at EOC. On the other hand, the MTC are highly negative even at BOC condition, about -56.55 pcm/K. It is advantageous that the difference in MTC between BOC and EOC is only 3.77 pcm/K, which simplify the reactivity control over the cycle of the core. The associated uncertainty of the FTC and MTC are 0.22 and 1.17 pcm/K, respectively. Overall, both FTC and MTC are all negative, assuring the inherent stability of the ATOM core at any condition.

Table V: FTC and MTC evaluation

Condition	FTC (pcm/K)	MTC (pcm/K)
BOC	-2.55 ± 0.22	-56.55 ± 1.17
EOC	-2.53 ± 0.22	-60.32 ± 1.17

4. Conclusions and Future Works

In this paper, the neutronic optimization of cylindrical CSBA for a three-batch TOP ATOM core is performed in terms of cycle length, discharge burnup, BRS, and peaking factor. The numerical results show that the target reactivity swing, about 1,000 pcm, is achieved to assure the SBF operation of the three-batch ATOM core. In addition, both radial and axial power distributions are favorable with relatively low peaking factors, especially for axial peaking. The axial CSBA zoning is successfully introduced to completely eliminate the axial power oscillation. Moreover, the discharge burnup of the core is highly competitive to that of the commercial PWRs thanks to the TOP lattice design. All in all, the three-batch SBF ATOM core has been successfully optimized by using 2-cylinder CSBA and TOP lattice.

On the other hand, the radial CSBA loading and fuel shuffling scheme should be further optimized to reduce the radial peaking. Moreover, as the MTC of the SBF SMRs is highly negative, designing a sufficient control rod pattern to assure cold shutdown is challenging and will be considered in the future study.

ACKNOWLEDGEMENT

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

REFERENCES

[1] X. H. Nguyen, C. Kim, and Y. Kim, "An advanced core design for a soluble-boron-free small modular reactor ATOM with centrally-shielded burnable absorber," Nuclear Engineering and Technology, vol. 51, pp. 369-376, 2019.

[2] M. S. Yahya and Y. Kim, "An innovative core design for a soluble-boron-free small pressurized water reactor", Int. J. Energy Res., 2017, pp. 1–9

[3] X. H. Nguyen, S. Wijaya, and Y. Kim, "Optimization of Two-batch Fuel Management in the Soluble-Boron-Free ATOM Core", Transactions of the KNS Spring Meeting, ICC Jeju, Korea, May 18-20, 2022.

[4] X. H. Nguyen, S. Wijaya, and Y. Kim, "Three-batch Soluble-Boron-Free ATOM Core Design with Pan-shape CS", ANS Winter Meeting & Expo, Nov. 30- Dec. 3, 2021, Washington D. C.

[5] J. Leppänen, M. Pusa, T. Viitanen, V. Valtavirta and T. Kaltiaisenaho, "The Serpent Monte Carlo code: status, development and applications in 2013," Annals of Nuclear Engergy, vol. 82, pp. 142-150, 2015.

[6] Westinghouse, "2.2: Power distribution limits R304P," US-NRC, Washington, 2021.

[7] K. S. Kim, T. J. S. G. Hong and J. W. Song, "Benchmark Matrix for Verification and Validation of the KARMA code," KAERI, Daejeon, 2010.