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Two Batch Fuel Management for the Soluble Boron Free ATOM Core

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1. Introduction

Small modular reactors (SMRs) are promising in terms of economics, multi-purpose capability, siting flexibility, and modular construction. In particular, operating the SMRs in remote or isolated locations under harsh conditions requires inherent safety and highly reliable system. To accomplish these requirements, SMRs should be compact, simple and less dependent on active control components. From this point of view, for pressurized water reactor (PWR) type SMRs with soluble boron free (SBF) coolant is favorable because the use of borated coolant has following drawbacks: 1) acceleration of material corrosion 2) radioactive liquid waste 3) positive moderator temperature coefficient, 4) complicated chemical volume control system (CVCS).

In previous work [1, 2], a 450MWth SBF SMR based on PWR type, namely autonomous transportable on-demand reactor module (ATOM), has been studied, aiming at extremely safe SMR with autonomous operation capability. To eliminate the soluble boron from the coolant without any degradation of the safety or performance, a new burnable absorber (BA) design, centrally-shielded burnable absorber (CSBA) was introduced and its neutronics feasibility of using a single batch fuel management was evaluated using optimized CSBA loading scheme.

The main purpose of this study is to evaluate the feasibility of two-batch fuel management in the ATOM core operation to enhance the fuel utilization.

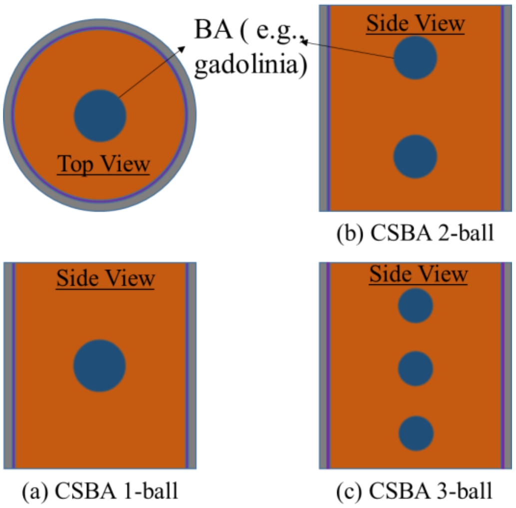
In the two-batch fuel management scheme, the location of fresh and once-burned fuel assemblies are optimized considering the burnup reactivity swing, fuel utilization, and radial power distribution. All the neutronics calculations are carried out using Monte Carlo code SERPENT2 in conjunction with ENDF/B-VII.1.

2. CSBA concept and ATOM core

2.1. CSBA concept

The CSBA is a ball-type burnable absorber, which is located inside of a fuel pellet as shown in Fig. 1. Three types of CSBA-loaded pellets were introduced depending on the number and size of CSBA in a pellet [3]. In order to minimize the burnup reactivity swing of ATOM core, a spherical CSBA has been considered for the maximum spatial self-shielding effect and slowest depletion rate. The self-shielding effect of CSBA can be manageable by adjusting the number and size of CSBA balls.

Gadolinia (Gd_2O_3) has been selected as a burnable absorber of CSBA concept due to its favorable neutronics and thermomechanical performances [4, 5]. Table I shows detailed information of CSBA corresponding to the CSBA types used in this study. The size of CSBA balls were determined by heuristic way to achieve a reactivity swing less than 2,000 pcm without any control rod movement. We assume that the maximum assembly-wise radial power peaking factor through all burnup steps should be less than 1.5.



(b) CSBA 2-ball
(a) CSBA 1-ball
(c) CSBA 3-ball

Fig. 1. CSBA-loaded fuel pellets

Since the CSBA balls are located at the center of fuel pellet, we expect that the CSBA can reduce the power peaking factor.

Table I. CSBA design parameter

CSBA design		FA zone		
		A	B	C
Case 1	CSBA type	1-ball	2-ball	2-ball
	Ball radius	1.60 mm	1.20 mm	1.20 mm
Case 2	CSBA type	2-ball	2-ball	2-ball
	Ball radius	1.27 mm	1.15 mm	1.15 mm

2.2. ATOM core

The CSBA-loaded 450MWth ATOM core is shown in Fig 2. A fully heterogeneous ATOM core model was used for burnup calculations in this study. Total 69 fuel assemblies are loaded into the ATOM core. Fuel assembly design is based on conventional 17x17 PWR lattice. Each fuel assembly has 264 CSBA fuel rods, 24 guide thimbles, and a central instrument tube, as shown in Fig. 3. The uranium enrichment of UO_2 pellet is 4.95 w/o with 95.5% theoretical density. The ATOM has the average power density of 25.99 W/gU and its active core height is 200 cm. Reflectors are comprised of stainless steel (no water-baffle), and axial fuel cutbacks of 5 cm are located at the top and bottom of the core.

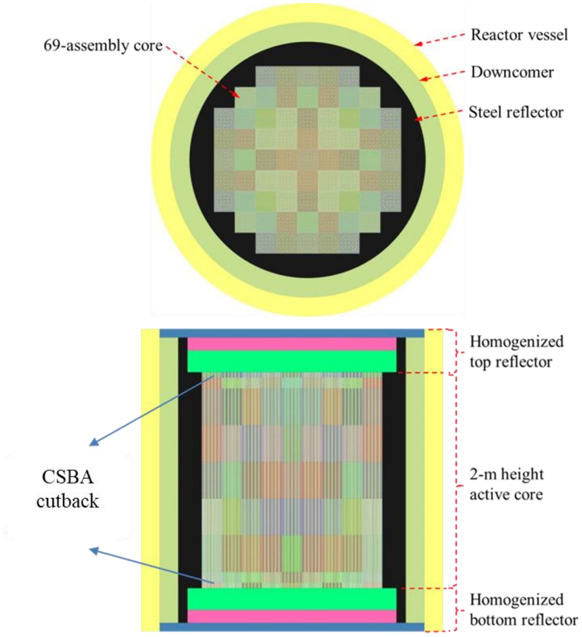


Fig. 2. Radial and axial layouts of ATOM core

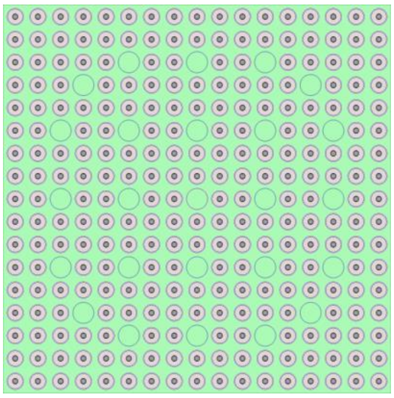
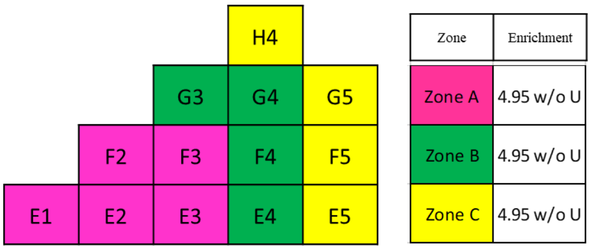


Fig. 3. 17x17 PWR fuel assembly with CSBA loading

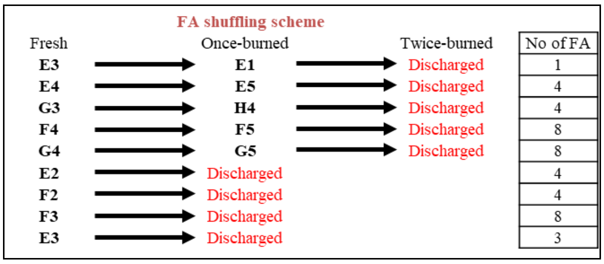
3. Two batch approach

Two batch fuel management was applied to the ATOM core to achieve ~30 month cycle length. In each burnup cycle, 44 fresh fuel assemblies and 25 once-burned fuel assemblies are arranged in the core. Twenty-four of the once-burned fuel assemblies are reloaded into the peripheral core region to reduce the neutron leakage out of the core and achieve the longer cycle length. The remaining (one) once-burned fuel assembly is located at the core center to reduce the radial power peaking. The two-batch fuel loading pattern and corresponding shuffling scheme of ATOM core are shown in Figs. 4 and 5, respectively.



Zone	Enrichment
Zone A	4.95 w/o U
Zone B	4.95 w/o U
Zone C	4.95 w/o U

Fig. 4. Zone-wise FA loading in 1/8 core symmetry



FA shuffling scheme

Fresh	Once-burned	Twice-burned	No of FA
E3	E1	Discharged	1
E4	E5	Discharged	4
G3	H4	Discharged	4
F4	F5	Discharged	8
G4	G5	Discharged	8
E2	Discharged		4
F2	Discharged		4
F3	Discharged		8
E3	Discharged		3

Fig. 5. Fuel assembly shuffling scheme for 2-batch

4. Numerical Results

Serpent2 code was used for all burnup calculations. The simulations was conducted by using total 50,000 neutron particles per cycle (300 active and 100 inactive cycles). Figures 6 and 7 shows burnup-dependent k-eff during equilibrium fuel cycle for ATOM core without and with CSBA loading, respectively. The differences in achievable burnup among the cases with different CSBA designs were not noticeable, but the case using only 2-ball CSBA design shows the highest burnup.

Figure 8 shows k-eff according to effective full power day (EFPD), and the evaluated excess reactivity and reactivity swings are summarized in Table II. It is clearly seen that the excess reactivity and reactivity swing can be drastically suppressed by using the CSBA. The case with 2-ball design in the central region (case 2) results in lower reactivity swing compared to that of using 1-ball design. In particular, the burnup of case 2 was quite close to the burnup without CSBA loading.

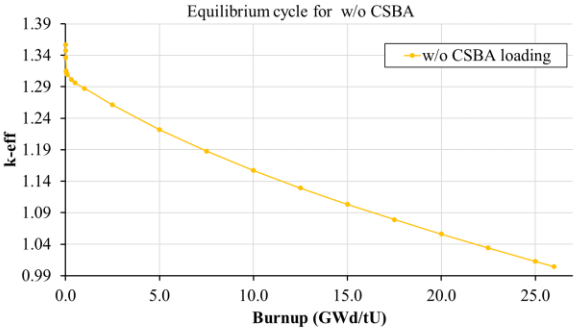


Fig. 6. Burnup-dependent k-eff of equilibrium cycle for ATOM core without CSBA loading

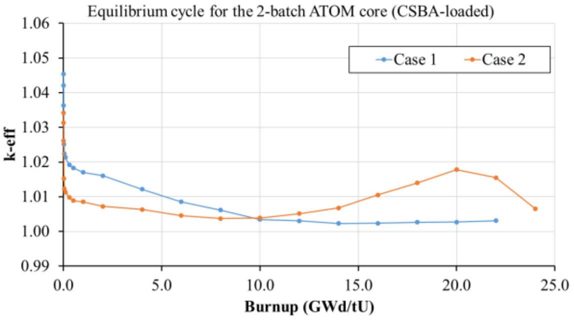


Fig. 7. Burnup-dependent k-eff of equilibrium cycle for ATOM core with CSBA loading

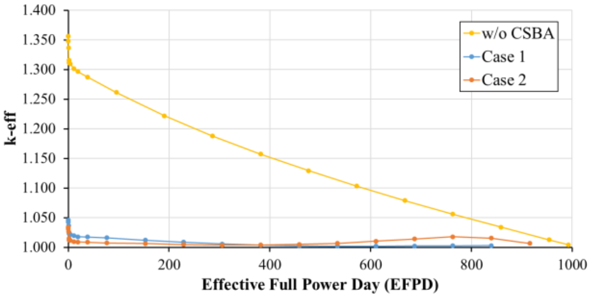


Fig. 8. k-eff depending on EFPD

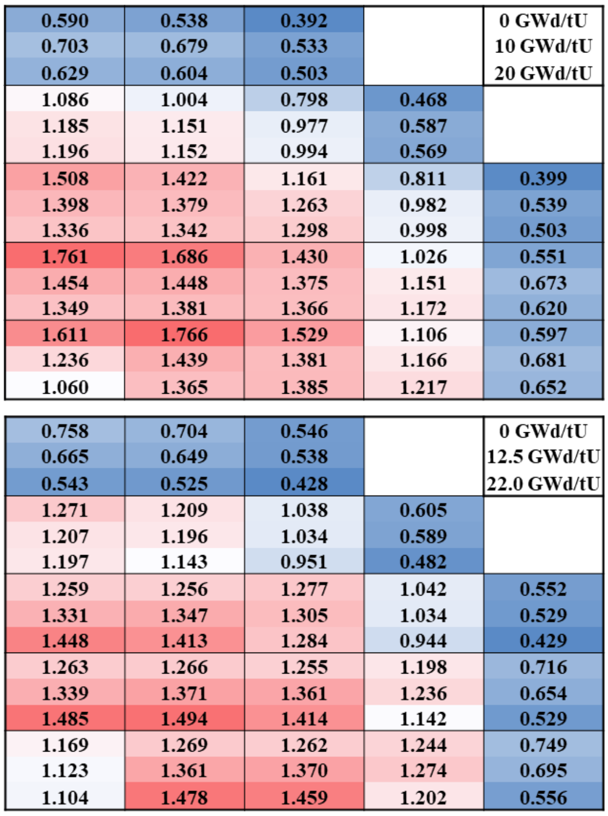
Table II. Excess reactivity at BOL and reactivity swing depending on CSBA loading

Case	Excess reactivity at BOL (pcm)	reactivity swing (pcm)	Fixed Cycle Burnup (GWd/tU)
w/o CSBA	26,283	22,300	25.5
Case 1	4,407	1,735	22.0
Case 2	3,293	1,722	24.0

Table III. Assembly-wise discharged burnup

Fresh FA	Discharged burnup (GWd/tU)		
	Num. of FA	Case 1	Case 2
E2	4	32.403	33.244
E3	4	32.419	34.320
E4	4	39.290	43.201
F2	4	32.119	33.351
F3	8	30.177	32.489
F4	8	37.957	42.220
G3	4	38.576	43.212
G4	8	31.980	36.360
Average		34.094	37.224

Assembly-wise discharge burnups are summarized in Table III. Compared to discharged burnup without CSBA loading (25.5 GWd/tU), we could obtain higher discharged burnup (34~37 GWd/tU) by applying the 2-batch fuel management in the ATOM core.



0.590 0.703 0.629	0.538 0.679 0.604	0.392 0.533 0.503		0 GWd/tU 10 GWd/tU 20 GWd/tU
1.086 1.185 1.196	1.004 1.151 1.152	0.798 0.977 0.994	0.468 0.587 0.569	
1.508 1.398 1.336	1.422 1.379 1.342	1.161 1.263 1.298	0.811 0.982 0.998	0.399 0.539 0.503
1.761 1.454 1.349	1.686 1.448 1.381	1.430 1.375 1.366	1.026 1.151 1.172	0.551 0.673 0.620
1.611 1.236 1.060	1.766 1.439 1.365	1.529 1.381 1.385	1.106 1.166 1.217	0.597 0.681 0.652

0.758 0.665 0.543	0.704 0.649 0.525	0.546 0.538 0.428		0 GWd/tU 12.5 GWd/tU 22.0 GWd/tU
1.271 1.207 1.197	1.209 1.196 1.143	1.038 1.034 0.951	0.605 0.589 0.482	
1.259 1.331 1.448	1.256 1.347 1.413	1.277 1.305 1.284	1.042 1.034 0.944	0.552 0.529 0.429
1.263 1.339 1.485	1.266 1.371 1.494	1.255 1.361 1.414	1.198 1.236 1.142	0.716 0.654 0.529
1.169 1.123 1.104	1.269 1.361 1.478	1.262 1.370 1.459	1.244 1.274 1.202	0.749 0.695 0.556

Fig. 9. Radial power distribution of 2-batch fuel management for CSBA-loaded ATOM core (Top: case 1, Bottom: case 2)

Figure 9 illustrates the radial power distribution after applying 2-batch fuel management. Since the once-burned FAs were loaded at the center position, the center power is relatively small compared with neighboring FAs. In this study, Case 2 satisfied the preliminary requirement (maximum assembly-wise radial peaking factor < 1.5) for ATOM core and had a small defect in burnup compared to that of the case without CSBA.

5. Conclusion

To achieve higher discharged burnup compared to previous single batch ATOM core design, the feasibility of applying 2-batch fuel management to the core was evaluated in this study. Noticeable improvement in discharge burnup with marginal reactivity penalty was observed using 2-batch fuel management in the ATOM core. It is necessary to optimize the design parameters of CSBA ball for 2-batch fuel management as further study. In addition, we contemplate to use beryllium reflector for the ATOM core to improve the neutron economy, and this also will be our future work.

6. Acknowledgements

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REFERENCES

[1] Xuan Ha Nguyen, Anisur Rahman, and Yonghee Kim, "CONCEPTS AND CHARACTERISTICS OF A SOLUBLE-BORON-FREE SMALL MODULAR REACTOR WITH CENTRALLY-SHIELDED BURNABLE ABSORBERS," PHYSOR 2018, Cancun, Mexico, April 22-26, 2018

[2] Xuan Ha Nguyen and Yonghee Kim, "A Monte Carlo-Diffusion Two-step Analysis of an Soluble-Boron-Free SMR Using Centrally-Shielded Burnable Absorber," Korean Nuclear Society Spring Meeting, Jeju, Korea, May 17-18, 2018

[3] M.S. Yahya and Y. Kim, “A Centrally-Shielded Burnable Absorber for LWR Fuel” Proceedings of ICAPP 2017, Fukui and Kyoto, Japan, 2017.

[4] 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. Jul; 53 7:1048-1060, 2016

[5] Galperin A., Segev M., Radkowsky A. “Substitution of the soluble boron reactivity control system of a pressurized water reactor by gadolinium burnable poisons”. Nucl. Tech; 75:127-133, 1986