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Multi-Physics Rodded Depletion of an Uprated Soluble-Boron-Free ATOM Core Design with Mode-Y logic

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1. Introduction

Recently, the research interest of the PWR-type Small Modular Reactor (SMR) has been increased due to the numerous advantages offered, such as, integrated and simplified system, enhanced safety, flexibility features, and well-matured PWR technology [1]. Furthermore, by eliminating the soluble boron from the core, the inherent safety is guaranteed with a clearly negative Moderator Temperature Coefficient (MTC) [2]. However, the smaller core size results in the higher neutron leakage; therefore, the uranium utilization is lower than the typical PWR [3]. In addition, the Soluble-Boron-Free (SBF) core results in a too much negative MTC; hence it will be a challenge to satisfy the necessary cold shutdown margin.

Recently, an enhanced-moderation Fuel Assembly (FA), so called Truly Optimized PWR (TOP) lattice, has been demonstrated to successfully increase the neutronic performance of the uprated SBF SMR, named Autonomous Transportable On-demand reactor Module (ATOM) [4]. The excess reactivity can be managed by utilizing an innovative cylindrical Centrally-Shielded Burnable Absorber (CSBA). While the axial power stability is ensured by utilizing a simple axial fuel enrichment zoning. In addition, the reactor cold shutdown condition is guaranteed by utilizing a checker-bard Control Rod (CR) pattern with extended Control Element Assembly (CEA).

This study is the continuation of the previous study, where a multi-physics calculation that couples the neutronic and thermal-hydraulics feedback is performed. Furthermore, to be more practical, the rodded depletion analysis is also performed. In this study, the well-known conventional two-step calculation is adapted. The FA homogenization was performed utilizing the continuous-energy Monte Carlo Serpent 2 Code in conjunction with the ENDF/B-VII.1 library [5,6]. While the in-house 3-D diffusion code, KAIST Advanced Nuclear Tachygraphy (KANT), was utilized to perform the 3-D whole core calculation [7]. Finally, the mode-Y logic is adapted for the rodded depletion to minimize the Axial Shape Index (ASI) value [8].

2. The ATOM Core Design

2.1 Truly Optimized PWR Lattice

The standard 17x17 FA design for PWR is optimized under the soluble-boron condition to assure a negative MTC during the whole reactor operation resulting in an under-moderated FA. In case of SBF condition, the Hydrogen to Uranium (HTU) ratio can be increased resulting in an enhanced moderation and higher reactivity. The softer neutron spectrum results in a sufficiently negative and similar MTC value throughout the reactor operation, which is favorable for a smaller temperature defect and larger cold shutdown margin, especially at the highly burned condition.

Based on the standard 17x17 FA, there are two ways to enhance the neutron moderation. First, by enlarging the pin pitch while fixing the fuel radius, and the second one is by reducing the fuel radius while preserving the FA size as illustrated in Figure 1.

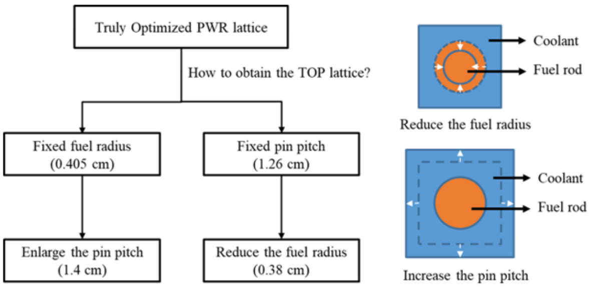
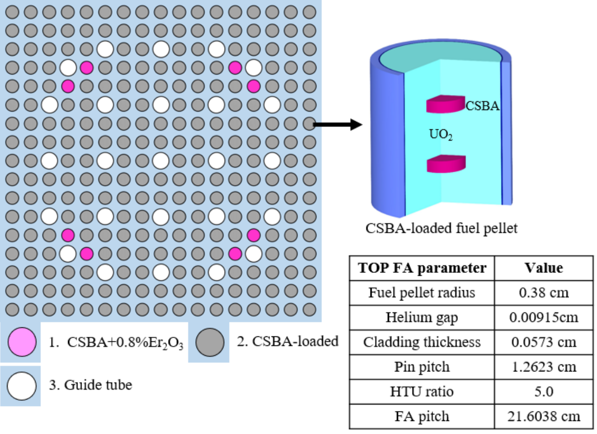


Fig. 1. TOP lattice designs.

In this study, the second approach, which used in the previous study, is implemented. The fuel radius is reduced to 0.38 cm with the fixed 1.26 cm pin pitch. The detailed design of the TOP FA is depicted in Figure 2.

Fig. 2. TOP CSBA-loaded FA design.



TOP FA parameter	Value
Fuel pellet radius	0.38 cm
Helium gap	0.00915cm
Cladding thickness	0.0573 cm
Pin pitch	1.2623 cm
HTU ratio	5.0
FA pitch	21.6038 cm

In this study, the TOP lattice with 5.0 HTU is utilized. Furthermore, the TOP lattice incorporates a small amount of Erbia (Er_2O_3) ~0.8% bearing fuel rods, neighboring the Guide Tube (GT), to reduce the early excess reactivity and the local pin power peaking factors.

2.2 Cylindrical CSBA Design

Generally, Gadolinia (Gd_2O_3) is utilized as the BA material due to the large neutron capture cross-section. However, the conventional 2-D BA design, such as gadolinia bearing fuel, depletes too quickly, making it difficult to manage the excess reactivity for whole reactor operation. Therefore, a 3-D cylindrical CSBA is proposed to manage the excess reactivity during the whole reactor operation. The cylindrical CSBA-loaded fuel pellet is depicted in Fig. 2.

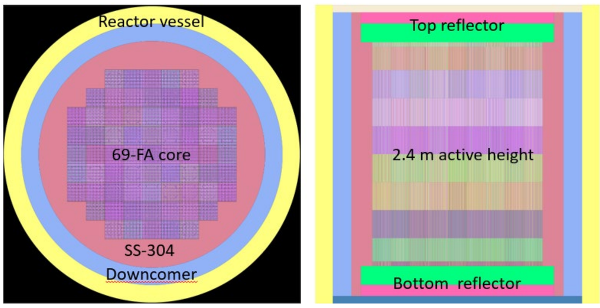
The self-shielding of the cylindrical CSBA is controlled by setting the number of the CSBA cylinders per fuel pellet while keeping the BA volumes, and by adjusting the cylinder's height-to-diameter (HTD) ratio. In this study, the 2-cylindrical CSBA design with 89% Theoretical Density (TD) of Monoclinic Gd_2O_3 is used as the primary means of reactivity control in the core.

2.3 ATOM Core Design

Table I: ATOM core design parameters

Parameter	Value
Thermal power	540 MWth
Fuel management	Two-batch
Active core height	240 cm
Targeted cycle length	2 years
FA type, number of FA	17x17, 69
Fuel density	95.5% TD
Radial reflectors	SS-304
BA design	Cylindrical CSBA
BA material	Monoclinic Gd_2O_3
BA theoretical density	8.33 g/cc
BA density	7.40 g/cc (0.89% TD)
Targeted reactivity swing	1,000 pcm
Inlet coolant temperature	295.7 ℃
Outlet coolant temperature	323 ℃

The ATOM core design parameters and schematic layouts are presented in the Table I and Fig. 3, respectively. The core is designed to operate at 540 MWth power and loaded with 69 TOP-based 17x17 FAs with an active core height of 240 cm. A 40 cm reflector is placed at the top and bottom of the core. The fuel management strategy adopts the two-batch scheme, with a targeted cycle length of two years. Each FA comprises of 264 fuel rods loaded with CSBA, 24 guide thimbles, and a central tube. Stainless-steel 304 (SS-304) is utilized as the radial reflector. The fuel enrichment is 4.95 w/o with 95.5% TD while a 5 cm blanket with 3.0 w/o enrichment is loaded at the top and bottom of the active core.



a. Radial view b. Axial view

Fig. 3. Schematic layout of the ATOM core (Serpent 2).

Figure 4 and Table II show the fuel loading pattern utilized in this study. An in-out fuel shuffling scheme is adopted to reduce the radial leakage and improve the neutron economy. Most of the feed FAs are loaded in the inner zone, while the once-burnt FAs are positioned in the peripheral zone. Several once-burnt FAs are loaded in the inner region to flatten the radial power distribution. The core has 34 standard feed FAs with 4.95 w/o UO_2, resulting in a rotationally symmetric core. Additionally, a special central with 3.0 w/o UO_2 is used to lower the central power peaking.

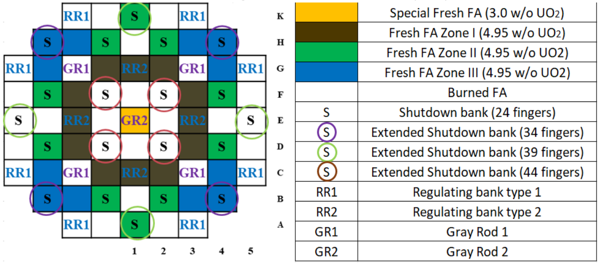


Fig. 4. Radial fuel-loading scheme and checker-board CR pattern.

Table II: The fuel shuffling scheme

Zone I		Zone II		Zone III	
Fresh	Burned	Fresh	Burned	Fresh	Burned
C2	A3	B2	A2	B3	H1
D3	C5	D4	D5	B4	C3
E3	D2	F4	F5	C4	E2
F3	G5	H2	K2	G4	E5
G1	F2	K1	E4	H3	F1
G2	K3			H4	G3

The CSBA is radially zoned to obtain a flat radial power distribution, as depicted in Figure 4. The largest cylindrical CSBA is loaded in the in the inner zone (Zone I) to lower the power peaking, while the smallest CSBA is loaded in the peripheral zone. Table III describes the CSBA parameters for each zone.

Table III: Radial zone-wise CSBA parameter

Parameter	Zone			
	I	II	III	Center
Diameter (mm)	3.09	2.66	2.42	2.66
Height (mm)	1.05	0.88	0.80	0.88
H/D ratio	0.34	0.33	0.33	0.33

The SBF operation has a clearly negative MTC since the Beginning of Cycle (BOC) resulting in a bottomskewed power distribution due to higher coolant density at the core bottom. Therefore, the fuel enrichment is zoned axially to obtain a favorable and stable axial power distribution. The lower half of the core has a lower fuel enrichment compared to the upper-half. The axial fuel enrichment zoning is shown in Table IV.

Table IV: Axial fuel enrichment zoning

Axial position (cm)	Zone			
	I	II	III	Center
235-240	3 w/o	3 w/o	3 w/o	3 w/o
120-235	4.95 w/o	4.95 w/o	4.95 w/o	3 w/o
5-120	4.79 w/o	4.78 w/o	4.79 w/o	3 w/o
0-5	3 w/o	3 w/o	3 w/o	3 w/o

The ATOM core checker-board CR pattern is illustrated in Figure 4, comprising of 20 shutdown CEAs, 12 regulating CEAs, and 5 gray CEAs. The Shutdown Rod (SR) is loaded with 90 w/o B-10 B_4C, while 50 w/o B-10 B_4C is adopted in the regulating rod. The 12 SRs are extended by utilizing the empty fingers in the neighboring FAs (34, 39, or 44 fingers) to improve the cold shutdown margin. The Gray Rod (GR) is adopted to attain core criticality while minimizing the distortion of the axial and radial power distribution. Therefore, the GR worth should be similar to the burnup reactivity swing. To lower the ASI value, A hybrid composition of Gray Rod 2 (GR2) is proposed. The GR2 consists of Manganese in the upper part (180 cm) and AIC in the lower part (60 cm). The upper part will have a smaller reactivity worth, while the lower part will have a higher worth. Thus, a smaller ASI value can be obtained. Table V provides a summary of the CR materials.

Table V: The CR material for the ATOM core

Parameter	Value
Shutdown rod material	90% B-10 B_4C
Regulating rod 1 material	50% B-10 B_4C
Regulating rod 2 material	50% B-10 B_4C
Gray rod 1 material	180 cm upper Manganese 60 cm lower AIC
Gray rod 2 material	Manganese

3. Numerical Results and Discussion

The Serpent 2 code is capable of handling any complex geometry model utilizing the constructive solid geometry and neutron physics interaction without any major approximation. Therefore, the heterogeneous lattice can be modeled accurately, generating a high-quality reference solution. The FA cross-sections (XSs) were generated with 250,000 neutron histories, 300 active and 150 inactive cycles with the associated K_{inf} uncertainty < 10 pcm.

The in-house KANT is capable of performing the multi-physics analysis where the neutronic solver is coupled with the assembly-wise thermal-hydraulics kernel. The 3-D neutronic solver is based on the Nodal Expansion Method (NEM) accelerated by either the Coarse Mesh Finite Difference (CMFD) or p-CMFD. While in the TH kernel, several assumptions are utilized, such as the cross-flow between the channels is ignored, no axial conduction in fuel and coolant, and the pressure drop in the coolant channel is neglected. The KANT code is well-verified with various benchmark problems, such as the NEACRP and KAIST SMR benchmark problem [7]. In addition, the rodded depletion calculation is performed with the CEA control logic named “Mode-Y” [8]. It should be noted that in this analysis, the CR is not depleted. Table VI tabulates the calculation parameters for the KANT TH-coupled analysis.

Table VI: KANT TH-coupled parameter

Parameters	**Conditions**
Number of radial mesh for fuel pin/gap/cladding for TH calculation	10/1/1
Mass flow rate	3,775 kg/s
Gap heat transfer rate	11,345 W/m^2K
Inlet coolant temperature	569.13 K
Neutronic solver	2x2 NEM
Axial mesh height (cm)	5
Cycle length (EFPDs)	709

To ensure the stability of the design, the rodded depletion calculation is performed up to 20 cycle. Figure 5 shows the last 4 cycle ASI value. We may observe the ASI is converged with the maximum ASI 0.155 during the cycle and -0.179 at the EOC due to the rod withdrawal.

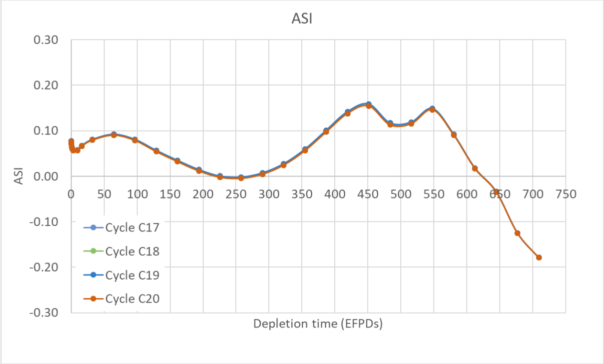


Fig. 5. Last six cycle ASI value

Figure 6 shows the summary of the CR movement. It should be noted that 40 cm is the bottom of the active core as we are considering 40 cm reflector at the bottom of the core.

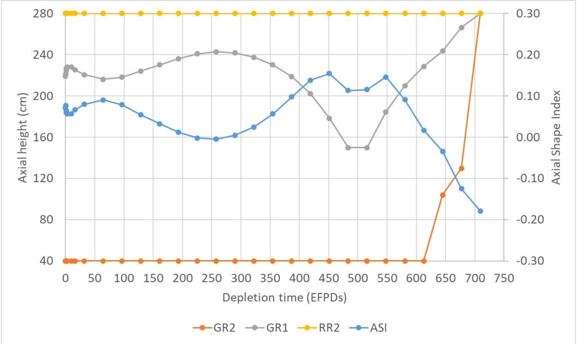
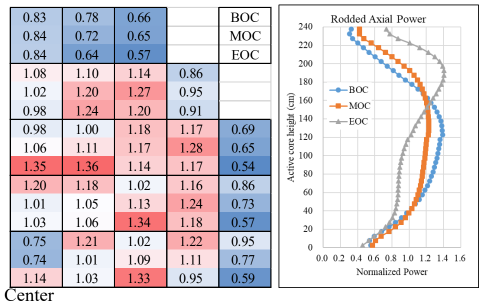


Fig. 6. Summary of the CR movement and ASI value

We may observe that the GR banks have enough worth to control the reactivity for the whole reactor operation. Figures 7 shows the radial assembly-wise and axial core-average power distribution of the rodded core.



0.83	0.78	0.66		BOC
0.84	0.72	0.65		MOC
0.84	0.64	0.57		EOC
1.08	1.10	1.14	0.86	
1.02	1.20	1.27	0.95	
0.98	1.24	1.20	0.91	
0.98	1.00	1.18	1.17	0.69
1.06	1.11	1.17	1.28	0.65
1.35	1.36	1.14	1.17	0.54
1.20	1.18	1.02	1.16	0.86
1.01	1.05	1.13	1.24	0.73
1.03	1.06	1.34	1.18	0.57
0.75	1.21	1.02	1.22	0.95
0.74	1.01	1.09	1.11	0.77
1.14	1.03	1.33	0.95	0.59

Center

Fig. 7. Radial and axial power of the rodded core

The maximum radial power is less than 1.36 while the maximum axial power is around 1.4. Figures 8 depicts the axial fuel and coolant temperature distribution of the rodded core.

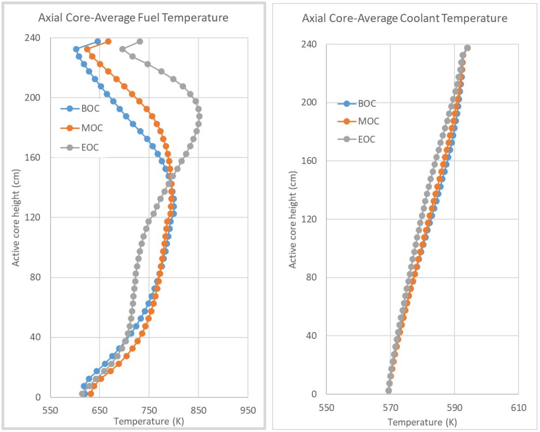
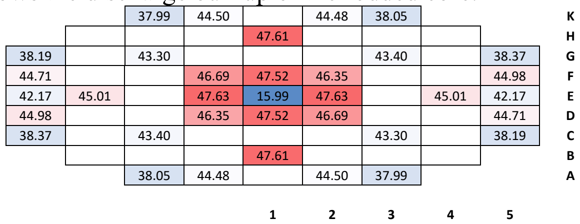


Fig. 8. Axial fuel and coolant temperature of the rodded core

The axial coolant temperature is linearly increased while the axial fuel temperature is following the axial power distribution of the associated cycle. Figure 9 shows the discharge burnup of the rodded core.



		37.99	44.50		44.48	38.05			K
				47.61					H
38.19		43.30				43.40		38.37	G
44.71			46.69	47.52	46.35			44.98	F
42.17	45.01		47.63	15.99	47.63		45.01	42.17	E
44.98			46.35	47.52	46.69			44.71	D
38.37		43.40				43.30		38.19	C
				47.61					B
		38.05	44.48		44.50	37.99			A
				1	2	3	4	5	

Average Discharge Burnup (GWd/ton)	42.80
Average Discharge Burnup Without Central FA (GWd/ton)	43.59
Minimum Discharge Burnup (GWd/ton)	15.99
Maximum Discharge Burnup (GWd/ton)	47.63

Fig. 9. Discharge burnup distribution of the rodded core

The average discharge burnup of the rodded core is relatively high compared to the standard 2-batch SMR core.

4. Conclusions

In summary, the multi-physic rodded depletion of the Uprated ATOM core has been successfully performed. It is observed that the GR banks have enough reactivity worth to control the reactor for the whole operation cycle. The CR movement and ASI is converged with the maximum ASI 0.155 during the reactor operation and -0.179 at EOC. Both the radial and axial power distribution is within the acceptable range as well as the axial fuel and coolant temperature. The discharge burnup is also relatively high compared to the standard 2-batch SMR core. Overall, the study demonstrates the practical and high performance SBF core design.

The CR design and loading pattern will be re-optimized aimed at further reduction of the ASI value. Additionally, an in-depth investigation of the hybrid CR worth will be carried out under various axial power shapes to comprehensively understand the CR behavior across different conditions. Furthermore, forthcoming work will involve start-up simulations and load-follow analyses to delve deeper into and explore the core's capabilities.

Acknowledgement

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