Application of Truly-Optimized PWR Lattice on the Soluble-Boron-Free Small Modular Reactor ATOM

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1. Introduction

The ideas of soluble-boron-free (SBF) light water reactors (LWRs) have been proposed since the 1980s [1]. However, SBF operation has not been practical due to low neutron economy and lack of a successful burnable absorber (BA) design that can maintain sufficiently small excess reactivity. Recently, the SBF operation has been renewed, particularly on PWR-type small modular reactors (SMRs). Numerous studies demonstrated that SBF operation is feasible since such excess reactivity can be achieved with newly-proposed BA designs [2] [3]. Nevertheless, the neutron economy still remains low because the most of recently proposed SMRs utilize the commercial PWR 17x17 fuel assembly (FA), which is neutronically optimal under soluble boron. It makes the SBF SMR are less competitive to Gen-III PWR. On the other hand, insufficient control rod (CR) worth is still a challenging issue for the SBF operation. To overcome this, the number of rodded FAs is increased [2], however it leads to a complicated CR mechanism due to space shortage at the top of the core. All in all, for practical SBF SMRs, the neutron economy of the core must be enhanced and simplified CR pattern is strictly required, e. g. checker-board pattern.

According to the ref. [4], it is demonstrated that the neutron economy can be maximized by slightly increasing the moderator-to-fuel ratio. In other words, fuel pin pitch is slightly increased to obtain optimal neutronics while maintaining the fuel rod diameter, so-called truly optimized PWR (TOP) lattice. In addition, larger coolant area (lower coolant speed) requires less pumping power and pressure drop are proportionally reduced. Therefore, passive safety features, natural circulation, and heat removal are enhanced during transients. However, a larger coolant area induces smaller critical heat flux, reducing the heat transfer coefficient, which must be taken into account in the selection of TOP.

In this paper, the TOP is applied to an SBF SMR, ATOM (Autonomous Transportable On-demand Reactor Module), with a fully two-batch fuel management (FM). The FM adopts an in-out shuffling scheme for further enhanced neutron economy. Moreover, to assure SBF operation in ATOM, the centrally-shielded burnable absorber (CSBA) design is utilized [5], in which 3-ball design is used. In addition, larger CR and checker-board CR patterns are proposed to assure the shutdown margin at cold-zero-power (CZP) condition. The one-rod-stuck scenario is also investigated. All of neutronic analyses, in this study, are performed by using the Monte Carlo Serpent 2 code [6] with nuclear library ENDF/B-VII.1. The numerical results reveal that the use TOP on the two-batch ATOM core increase discharge burnup and cycle length significantly, while radial peaking factor is considerably small. The temperature coefficients are highly negative assuring the inherent safety and favorable for passively autonomous power maneuvering. In addition, the proposed simplified CR pattern shows enough shutdown margin at CZP, even with one-rod-stuck scenario.

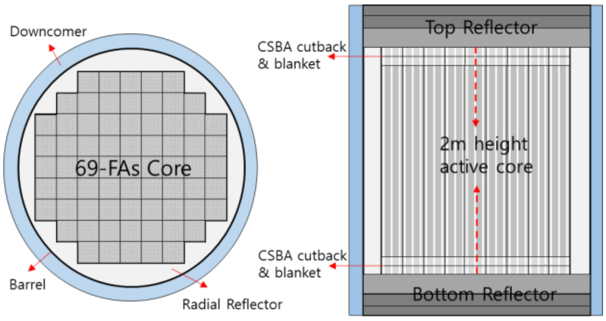
2. The ATOM Core Design

The major design parameters and cross-sectional views of ATOM core are presented in Table I and Fig. 1. The active core consists of 17x17 69 fuel assemblies (FAs) and 264 CSBA-loaded fuel rods are placed in each FA. The enrichment of UO_2 fuel is 4.95 w/o with 95.5 theoretical density. At the top and bottom of the active core, 5 cm UO_2 blankets with enrichment of 2.0 w/o and BA cutbacks are utilized. The core is designed to produce 450 MWth with a two-batch FM. The number of fresh and burned FAs are 35 and 34. To achieve reactivity swing smaller than 1,500 pcm, 3-ball CSBA design is adopted [5]. The TOP pin pitch is 1.40 cm, while the fuel pellet radius in this study is the same with that of commercial 17x17 PWR design. In addition, the accident-tolerant-fuel (ATF) cladding, Cr15Al-coated Zir-4, is used for improved safety of the reactor [7].

Table I: The ATOM core design specification.

Parameters	Value
Thermal power	450 MWth
Fuel materials, enrichment	UO_2, 4.95 w/o
FM (equilibrium)	Two-batch
No. of feed/burned FA	35/34
Radial reflectors	SS-304
BA design	3-ball CSBA
BA material	99% TD Gd_2O_3*
FA type, number of FA	17 x 17, 69
ATF cladding	Cr15Al-coated Zir-4
Pin pitch (cm)	1.40 cm
Reactivity swing (target)	1,500 pcm

**TD: theoretical density*



a) Radial layout b) Axial layout

Fig. 1. The axial and radial layouts of the ATOM core

For enhanced neutron economy, the two-batch ATOM core utilizes in-then-out fuel shuffling schemes as shown in Fig. 2 and Table II. Feed FAs are loaded in the inner regions while burned FAs are located mostly in the periphery regions. Several burned FAs are placed in the inner core for a flat radial power profile. The number of feed FA, 34, is equal to that of burned FA loaded with 4.95 w/o UO_2, while the special fresh FA at the center core are loaded with 3.0 w/o UO_2.

Table II: Fuel shuffling scheme of the ATOM core

Zone I		**Zone II**		**Zone III**		**Zone IV**	
F	**B**	**F**	**B**	**F**	**B**	**F**	**B**
G5	G7	G6	K7	K5	E8	H7	F5
F6	H8	F7	G9	H6	K6	G8	E9
E7	C7	D7	C9	F8	F9	C8	E6
D6	A8	C6	A7	D8	D9	B7	H5
				B6	A6		

F: replacing Feed FA; B: replaced Burned FA

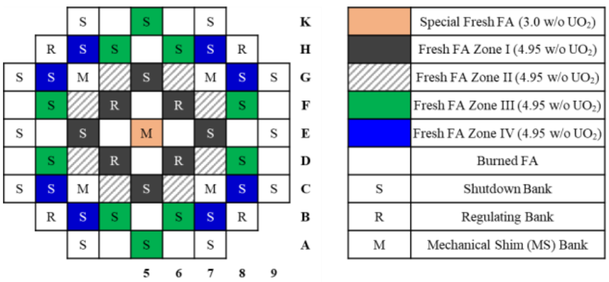
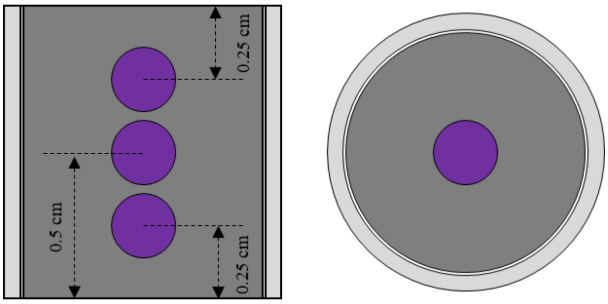


Fig. 2. Radial zone-wise fuel loading and CR pattern.

The detailed CR design for the TOP ATOM core is presented in Table III and Fig. 2. The control rod pattern comprises 35 shutdown FAs, 8 regulating FAs, and 5 mechanical shim FAs, respectively. The CR is bigger compared to the standard one for improved CR worth. 95 w/o B-10 B_4C is used as material for shutdown rod, while regulating and MS rod are natural B_4C and SS-304 doped Hf. The use of SS-304 is to reduce MS rod worth in order to minimize power distortion during criticality attainment.

Table III: The CR design for the 2-batch ATOM core

Parameters	Value
CR radius (cm)	0.51674
CR gap radius (cm)	0.52055
CR clad radius (cm)	0.56754
Inner tube radius (cm)	0.63679
Outer tube radius (cm)	0.69700
Shutdown rod material	95 w/o B-10 B_4C
Regulating rod material	Natural B_4C
MS material	SS-304 doped 2.5 w/o Hf



a) Axial layout b) Radial layout

Fig. 3. 3-ball CSBA fuel pellet.

In order to achieve SBF operation, the BA design plays a critical role in obtaining small burnup reactivity swing, which minimizes the movement of CR during operation. In the ATOM core, advanced BA design, CSBA, is used to achieve an SBF operation, as it is superior in reactivity management [5]. Only 3-ball CSBA design is used in two-batch FM to minimize the self-shielding effect as shown in Fig. 3. The CSBA loading pattern is shown in Table IV. To flat radial power distribution, the biggest CSBA ball is loaded into the inner regions, Zone I, while the smaller ball is placed in the outer regions. The CSBA design in the center FA, zone V, is the same with that in zone IV, except for the lower enrichment of 3.00 w/o.

Table IV: Zone-wise CSBA loading strategy

Zone	Design	CSBA radius	Fuel Enrichment
I	3-ball	1.20 mm	4.95 w/o
II	3-ball	1.10 mm	4.95 w/o
III	3-ball	1.06 mm	4.95 w/o
IV	3-ball	0.98 mm	4.95 w/o
V	3-ball	0.98 mm	3.00 w/o

3. Numerical Results and Discussion

To investigate the neutron performance of the ATOM core, the Monte Carlo Serpent 2 core is used in conjunction with the library ENDF/B-VII.1. The number of active and inactive cycles are 300 and 100, respectively, with 300,000 histories per cycle. The associated uncertainty of the multiplication factor is about 10 pcm while the associated uncertainty of power is 0.2%. In the equilibrium calculation, the effective temperatures of the fuel and coolant are 840K and 575K, respectively [8]. While the temperature at CZP and hot-zero-power (HZP) are 294K and 558K, respectively.

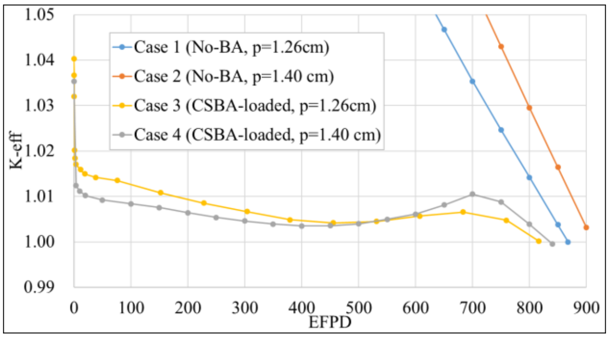


Fig. 4. The effective multiplication factor behavior of the ATOM cores

The neutronic performance of the ATOM equilibrium cycle is shown in Fig. 4 and Table V. It can be seen that the cycle length of the TOP cores is significantly enhanced compared to that of the standard core with the pitch of 1.26 cm. Without BA, the cycle length is increased by about 45 effective full power day (EFPD), while the cycle length increase by around 23 EFPD with CSBA. Similarly, the cycle burnup and discharge burnup gain with TOP are about 1-2 GWd/tU. In addition, the reactivity swing is less than 1,500 pcm for CSBA-loaded cores during the cycle. Note that the reactivity swing is the maximum excess reactivity after xenon equilibrium. A small reactivity is very favorable for the SBF operation with minimized movement of the CR [5]. The assembly-wise radial and axial power profile of the CSBA-loaded TOP core are depicted in Figs. 5 and 6. The peaking factor is quite small, about 1.5 at EOC condition, even though the fuel shuffling is based on an in-out scheme. In addition, the axial peaking factor is about 1.42 at MOC condition.

Table V: Neutronic performance of the ATOM cores

Case	ρ_{swing} (pcm)	Cycle length (EFPD)	Cycle burnup (GWD/tU)	Discharge burnup (GWd/tU)
1	-	868	22.4	44.1
2	-	913	23.6	46.5
3	1,473	817	21.5	42.8*
4	1,040	840	22.2	44.3*

**excludes the center FA*

The temperature coefficients of the TOP ATOM core for various conditions are listed in Table VI. The MTC and fuel temperature coefficients are highly negative at any condition, except for CZP, assuring the inherent safety feature of the core during operation. The positive MTC at CZP is not a safety concern because the reactor is at a shutdown state. One should note that the variation of MTC at hot-full-power (HFP) condition is only about -7 pcm/K between BOC and EOC, while it is about -14 pcm/K with standard pitch design [5]. The small variation of the MTC during a cycle is highly advantageous for minimization of control movement that is the major mean to compensate the negative reactivity feedback. In addition, such MTC values are favorable for the autonomous operation of the reactor [9]. In temperature coefficient evaluation, the associated uncertainties of FTC and MTC are 0.08 pcm/K and 0.30 pcm/K, respectively.

		0.551 0.520 0.482	0.748 0.676 0.619	0.850 0.764 0.763	0.754 0.679 0.620	0.550 0.523 0.489		BOC MOC EOC
	0.610 0.611 0.554	1.107 1.068 1.115	1.200 1.137 1.281	1.230 1.050 0.974	1.203 1.150 1.282	1.107 1.076 1.116	0.605 0.612 0.558	
0.556 0.544 0.455	1.111 1.106 1.094	1.109 1.053 0.975	1.201 1.201 1.479	1.155 1.147 1.436	1.205 1.225 1.468	1.112 1.078 0.982	1.102 1.106 1.087	0.548 0.537 0.450
0.778 0.732 0.559	1.189 1.240 1.255	1.190 1.266 1.470	1.152 1.185 1.411	1.277 1.186 1.042	1.152 1.201 1.398	1.195 1.272 1.459	1.188 1.246 1.231	0.777 0.728 0.547
0.891 0.831 0.575	1.181 1.270 1.030	1.128 1.235 1.453	1.274 1.205 1.041	1.077 1.221 1.035	1.281 1.205 1.036	1.125 1.231 1.436	1.182 1.269 1.015	0.890 0.829 0.560
0.773 0.741 0.558	1.182 1.259 1.268	1.189 1.293 1.496	1.156 1.222 1.431	1.291 1.213 1.047	1.164 1.215 1.414	1.194 1.287 1.471	1.184 1.256 1.239	0.779 0.735 0.551
0.546 0.548 0.460	1.096 1.135 1.123	1.107 1.110 1.012	1.203 1.268 1.507	1.157 1.198 1.457	1.218 1.262 1.493	1.116 1.086 0.983	1.100 1.119 1.093	0.550 0.545 0.450
	0.604 0.630 0.578	1.102 1.115 1.152	1.197 1.206 1.320	1.222 1.108 1.003	1.201 1.194 1.315	1.109 1.102 1.134	0.606 0.621 0.558	
		0.544 0.544 0.496	0.744 0.713 0.637	0.839 0.805 0.786	0.745 0.711 0.638	0.543 0.543 0.496		

Fig. 5. Radial assembly-wise power distribution of the ATOM core

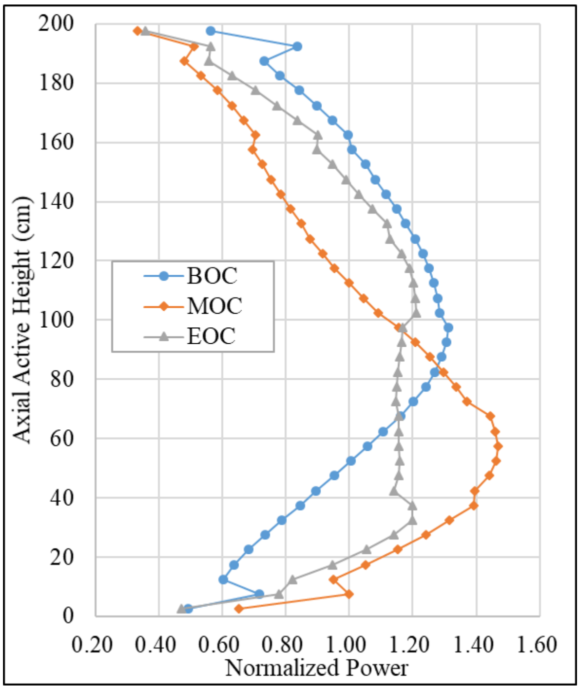


Fig. 6. Axial power distribution of the ATOM core

Table VI: Temperature coefficient at various conditions

Condition	MTC (pcm/K)	FTC (pcm/K)
HFP-BOC	-36.67	-2.06
HZP-BOC	-32.14	-2.30
CZP-BOC	2.29	-2.36
HFP-EOC*	-43.43	-2.39
HZP-EOC*	-37.20	-2.58
CZP-EOC*	2.33	-2.72

EOC: @ 700 EFPD near EOC*

Table VII: Shutdown margin of the TOP ATOM core

Scenario (@ CZP)	BOC, No Xenon		EOC*, No Xenon	
	K-eff	Rod Worth (pcm)	K-eff	Rod Worth (pcm)
ARO	1.09059	-	1.10236	-
ARI	0.95729	12,767	0.93275	16,496
N-1 (E5)	0.96532	11,899	0.94215	15,426
N-1 (F6)	0.96522	11,910	0.99111	10,183
N-1 (E7)	0.97947	10,403	0.98836	10,464
N-1 (F8)	0.97009	11,390	0.97411	11,944
N-1 (G7)	0.95788	12,704	0.93604	16,119

EOC*: @ 700 EFPD near EOC

The shutdown margin of the TOP ATOM core is tabulated in Table VII, including one-rod-stuck scenario (N-1 cases) at the various position. The shutdown evaluation is evaluated at both CZP-BOC and CZP-EOC* conditions without Xenon equilibrium. At all rod out (ARO), the excess reactivities are 8,306 pcm (k_{eff}=1.09059) and 9,286 pcm (k_{eff}=1.10236) corresponding to BOC and EOC*, which must be compensated by CR. It can be seen from the table that the proposed CR pattern shows enough rod worth to assure the core subcritical at any scenario with the conservative assumption of 10% uncertainty of the evaluation even though the number of rodded FA is reduced compared to that in the standard pin pitch [5]. Further CR design optimization needs to be done to achieve a checker-board pattern.

4. Conclusions

In this paper, the application of the TOP design optimization on the two-batch ATOM core is neutronically investigated. The numerical results show that with TOP, the cycle length and discharge burnup of the core is significantly enhanced compared to the standard one, which can eliminate the disadvantage of low neutron economy of SMR. In addition, the SBF operation is assured with the proposed CSBA loading strategy with a small reactivity swing during the cycle and acceptable peaking factors. It is demonstrated that the use of CSBA is superior in terms of the minimization of both excess reactivity and power peaking. Moreover, the use of TOP FA results in desirable MTC and FTC for power maneuvering and autonomous operation, while the shutdown margin is guaranteed with smaller number of rodded FA compared to standard ones. Nevertheless, further optimization of the CR pattern is needed for more practical SBF SMR.

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