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Optimization of Two-batch Fuel Management in the Soluble-Boron-Free ATOM Core

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1. Introduction

Recently, the research interests have kept increasing on PWR-type Small Modular Reactors (SMRs) because of well-matured PWR technology, system simplicity, short-time construction, siting flexibility, etc. [1]. However, low neutron economy and near positive Moderator Temperature Coefficient (MTC) are still the main obstacles to these SMRs. As such, the Soluble-Boron-Free (SBF) SMRs have been proposed to guarantee the inherent safety with a clearly negative MTC [2] [3]. Nevertheless, the current SBF SMRs have faced two main challenges: low economy and insufficient cold shutdown margin due to the too much negative MTC [3] [4] [5]. The cold shutdown is only assured if the fraction of the rodded FA is substantially increased, which leads to an impractically complicated control driving mechanism.

Recently, a SBF SMR, named autonomous transportable on-demand reactor module (ATOM), has successfully introduced an optimal enhanced-moderation Fuel Assembly (FA), so called Truly-Optimized PWR (TOP) lattice, to maximize the neutron economy [6]. Due to enhanced moderation, MTC becomes less negative and hence cold shutdown margin is improved. The optimal hydrogen-to-uranium (HTU) ratio in the TOP lattice was obtained by either enlarging the pin pitch or reducing the fuel pellet radius. In this study, the TOP lattice is achieved by reducing the pellet radius while preserving FA size, which is then utilized in the two-batch ATOM core.

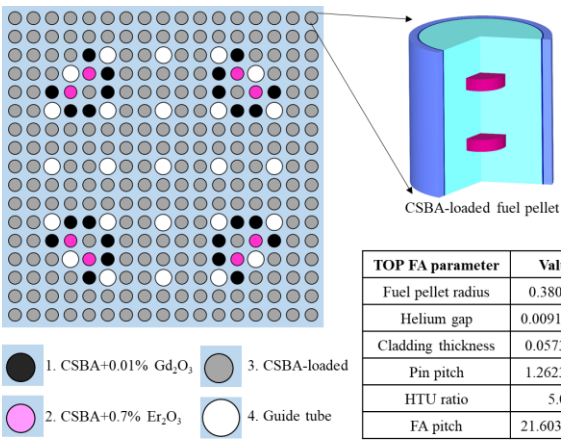
To assure a small reactivity swing for SBF ATOM, cylindrical Centrally-Shielded Burnable Absorber (CSBA) is used in an assembly-wise BA loading scheme. In addition, axial BA zoning is applied to assure a favorable and stable axial power profile. A checker-board Control Rod (CR) pattern with extended CEAs is introduced to guarantee the cold shutdown. In addition, a Gray Rod (GR) is designed to have a similar worth to reactivity swing so the criticality is obtained by the use of GR only. All of the calculations are performed by using the Monte Carlo Serpent 2 code with ENDF/B-VII.1 nuclear library [7].

2. The ATOM Core Design

2.1 Truly-optimized PWR Lattice

Most of the current SBF SMRs deploy the standard 17x17 FA to reduce fuel costs and to shorten licensing [8]. Nevertheless, the standard FA is only optimal under soluble boron condition leading to a low neutron economy. Hence, an enhanced moderation FA design is favorable as it improves the neutron economy, while providing more favorable MTC [6].

Based on the standard 17x17 FA [8], there are two ways to enhance the neutron moderation. The first one is to enlarge the pin pitch and FA size while keeping the fuel radius as demonstrated in the reference [6]. This modification is feasible for new reactor concepts, such as SMRs, because the SMR size is smaller than the current commercial PWRs. The second way is to reduce the fuel radius while preserving the FA size. However, the fuel inventory decreases significantly and the specific power density increases proportionally, which may result in a high peaking power. In this paper, the impacts of reduced fuel pellet design on the current commercial FA size in terms of neutronics are investigated and the detailed TOP FA is shown in Fig. 1.



TOP FA parameter	Value
Fuel pellet radius	0.380 cm
Helium gap	0.00915 cm
Cladding thickness	0.0573 cm
Pin pitch	1.2623 cm
HTU ratio	5.0
FA pitch	21.6038 cm

Fig. 1. The TOP CSBA-loaded FA design

It was demonstrated that the optimal HTU ratio is about 5.7 with an enlarged pin pitch while the standard one is about 4.1 [6]. However, the same condition cannot be applied for the reduced fuel TOP design. The fuel inventory reduction may outweigh the improved neutron economy. Therefore, the reduced fuel radius is selected based on the following design criteria:

- The HTU ratio is selected between 4.1 and 5.7 for an improved neutron economy.

- The cycle length is more than two years for two-batch fuel management.
- The MTC is sufficiently negative to ensure the inherent safety while minimizing the temperature defect for a practical CR pattern.

In addition, to control early excess reactivity, the TOP lattice utilizes Gd_2O_3- and Er_2O_3-bearing fuel rods. These fuel rods are placed neighboring to the guide tube to reduce local peaking factors further.

2.2 The 3-D Cylindrical CSBA Design

Gadolinia, Gd_2O_3, is the proven BA material in LWRs, which is effective in controlling the core reactivity. Nevertheless, it is challenging to achieve a small burnup reactivity swing for SBF operation with the conventional 2-D BA designs, e. g. gadolinia bearing fuel, due to the BA fast depletion at early burnup condition [8]. In this paper, a recently-proposed innovative 3-D cylindrical CSBA design is utilized to achieve a small reactivity swing for the two-batch ATOM core. The BA design was demonstrated to be highly neutronically flexible [8]. The cylindrical CSBA-loaded fuel pellet is depicted in Fig. 1.

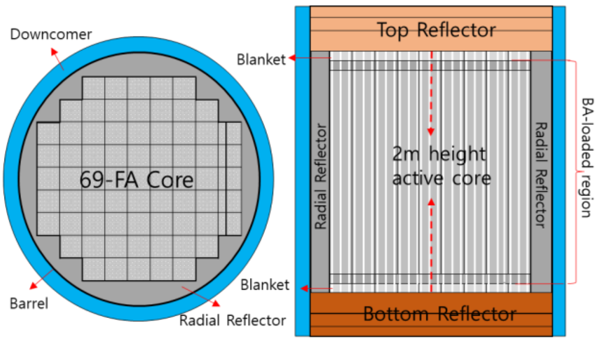
Like spherical CSBA, the self-shielding of the cylindrical CSBA-loaded pellet can be manipulated by adjusting the number of CSBA cylinder per pellet. However, the cylindrical CSBA is even more neutronically flexible than the spherical one as the spatial self-shielding effect can be adjusted further by modifying its aspect ratio, height-to-diameter (HTD) ratio. In this study, the 2-cylinder CSBA design with a pan-shape geometry is used as it was neutronically proved to be better than the pencil-shape one [8]

2.3 The ATOM Core Design

Table I: Major design parameters of the ATOM core

Parameter	Value
Thermal output	450 MWth
Core active height	200 cm
Fuel management	two-batch
Target cycle length	two years
FA type, number of FA	17×17, 69
Fuel material, enrichment	UO_2, 4.95 w/o
Fuel density	95.5% TD
Radial reflectors	SS-304
BA designs	2-cylinder CSBA
Gd_2O_3 density in CSBA	95% TD
No. of fresh/burned FAs	35/34
Coolant density at 582.5K	0.706 g/cm^3
Burnup reactivity swing	< 1,000 pcm

Major design parameters and schematic layouts of the two-batch ATOM core are listed in Table I and Fig. 2, respectively. The core is designed to have a 450 MWth power and it is loaded with 69 TOP-based 17x17 FAs with an active height of 200 cm. All FAs comprise 264 CSBA-loaded fuel rods, 24 guide thimbles, and a central tube. The core utilizes stainless steel as the radial reflector. The fuel enrichment is 4.95 w/o with 95.5% theoretical density (TD). At the top and bottom of the active core, a 5 cm blanket with 3.0 w/o enrichment is placed. Based on the linear reactivity model [6], the target cycle length, two years, can be achieved with the 0.38 cm fuel pellet radius corresponding to a HTU ratio of 5.0. The fuel inventory is about 14% smaller than the core with the standard one.



a) Radial layout b) Axial layout

Fig. 2. Radial and axial core configuration.

The fuel loading pattern is presented in Fig. 3 and Table II. For an improved neutron economy, an in-then-out fuel shuffling scheme is adopted. Most feed FAs are located in the inner positions while once-burnt FAs are placed in the periphery to minimize neutron leakage. To reduce the central power peaking, a few burned FAs are placed in the inner regions. Special central FA loaded with 3.0 w/o UO_2 is utilized to lower the central power peak further. The number of standard feed FAs is 34 with 4.95 w/o UO_2, resulting in a rotationally symmetric core. The feed FAs are radially divided into three zones, except the central one.

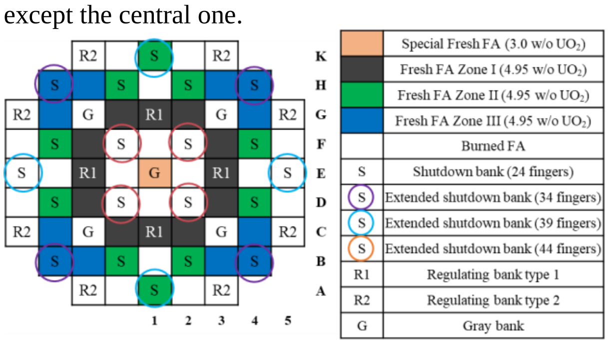


Fig. 3. Radial fuel scheme and checker-board CR.

Table II: The fuel shuffling scheme

Zone I		Zone II		Zone III	
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

Figure 3 also shows a checker-board CR pattern of the ATOM core and the CR design specification are listed in Table III. The CR pattern consists of 20 shutdown control element assemblies (CEAs), 12 regulating CEAs, and 5 gray CEAs. The shutdown rod utilizes B_4C with 90 w/o B-10 as the absorber, while 50% B-10 B_4C is adopted in the regulating rod. To enhance the cold shutdown margin, 12 shutdown CEAs are extended, which have either 34, 39, or 44 fingers by utilizing fingers in the neighbor FAs. The GR is a means to attain the core criticality without significant power distortion. To design the GR worth similar to the burnup reactivity swing, the Manganese is adopted as the GR material.

Table III: The CR specification for the ATOM core

Parameter	Value
Shutdown rod material	90% B-10 B_4C
Regulating rod material 1	50% B-10 B_4C
Regulating rod material 2	50% B-10 B_4C
GR material	Manganese

The radial CSBA pattern for the ATOM core is shown in Fig. 3 and Table IV. The largest cylindrical CSBA is placed in an inner zone, zone I, to lower the power peaking. Meanwhile the smallest CSBA is loaded to the outer regions. The appropriate HTD ratio for the core is about 0.3 to 0.45. The central FA is loaded with a unique cylindrical CSBA to control the central peaking factor. Unlike commercial PWRs, the SBF operation has clearly negative MTC at BOC, which results in highly bottom-skewed power distribution due to the higher coolant density at the bottom of the core. Therefore, an axial BA zoning is applied to pursue a favorable axial power distribution, as listed in Table V. The amount of BA for the lower half is slightly lower than the upper one. Meanwhile, the BA amount is much lower at the top and bottom active core to minimize the residual BA here.

Table IV: Radial zone-wise CSBA design

Parameters	Zone			
	I	II	III	Center
Diameter (mm)	3.33	2.68	2.46	2.37
Height (mm)	1.00	0.94	0.86	1.07
HTD ratio	0.30	0.35	0.35	0.45
V_{CSBA} (mm^3)	8.70	5.30	4.10	7.80

Table V: Axial CSBA volume zoning

Axial position (cm)	Zone I	Zone II	Zone III
175-195	$V_{BA} = 0.86V_{BA}^{Zone\ I}$	$V_{BA} = 0.89V_{BA}^{Zone\ II}$	$V_{BA} = 0.95V_{BA}^{Zone\ III}$
100-175	$V_{BA} = 0.98V_{BA}^{Zone\ I}$	$V_{BA} = 0.96V_{BA}^{Zone\ II}$	$V_{BA} = 0.95V_{BA}^{Zone\ III}$
25-100	$V_{BA} = 1.00V_{BA}^{Zone\ I}$	$V_{BA} = 1.00V_{BA}^{Zone\ II}$	$V_{BA} = 1.00V_{BA}^{Zone\ III}$
5-25	$V_{BA} = 0.89V_{BA}^{Zone\ I}$	$V_{BA} = 0.92V_{BA}^{Zone\ II}$	$V_{BA} = 1.00V_{BA}^{Zone\ III}$

3. Numerical Results and Discussion

The Monte Carlo Serpent 2 code [7] is used in conjunction with the library ENDF/B-VII.1 to investigate the neutronic performance of the ATOM core. There are 100,000 histories per cycle with 200 active cycles and 100 inactive cycles. The uncertainty of the effective multiplication factor (k_{eff}) is about 30 pcm. In the calculations, the effective fuel temperature is fixed at 900K. A linearly-varying axial coolant temperature from the bottom to the top of the core is considered with an average coolant temperature of 582.5K. Temperatures corresponding to CZP and hot zero power (HZP) are 298K and 582.5K, respectively. The ATOM core adopts a constant average coolant temperature between HZP and hot full power (HFP) conditions.

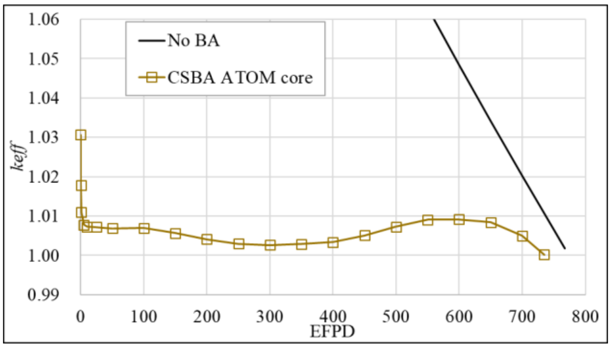


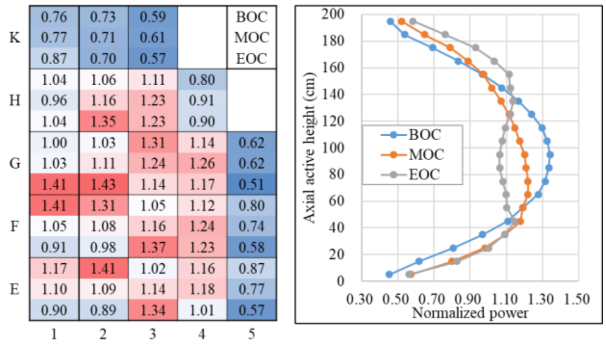
Fig. 4. The k_{eff} evolution for the equilibrium cores

The neutronic performances of several equilibrium cycles are shown in Fig. 4 and Table VI. It can be clearly seen that the burnup reactivity swing is successfully minimized by using the CSBA. The ATOM core has less than 1,000 pcm reactivity swing while the cycle length is about two years as targeted. It should be noted that the reactivity swing is defined as the maximum reactivity after xenon equilibrium. Meanwhile the discharge burnup, 44 GWd/tU, is quite comparable to 3-batch PWRs.

Table VI: Neutronic performance of the ATOM core

Case	ρ swing	Cycle length	Discharge burnup
No BA	-	767 days	45.3 GWd/tU
CSBA	908 pcm	735 days	44.3 GWd/tU

The power distribution is depicted in Fig. 5. One can see that the radial peaking is relatively low, about 1.40 at the End Of Cycle (EOC) condition, albeit the core adopts a low-leakage configuration. Meanwhile, the small axial peaking, about 1.3, can be found at BOC condition, when the axial power shape is just slightly bottom-skewed thanks to the small CSBA at the bottom of the core. At Middle Of Cycle (MOC), it becomes more bottom-skewed, while a typical saddle shape is observed at EOC condition. The associated uncertainties of the axial and radial power are 0.2% and 0.5%.



a) Radial power b) Axial power

Fig. 5. Axial core-average and radial assembly-wise power distribution of the ATOM core.

The temperature coefficients of the ATOM core for various conditions are tabulated in Table VII. One can see that the MTC at HFP, less than -53.9 pcm/K, is strongly negative at any condition. Moreover, the variation of the MTC at HFP between BOC and EOC is minor, about -8 pcm/K. Advantageously, the ATOM core is inherently stable regardless of the burnup condition. Therefore the reactivity and power control schemes are much more simplified. In the evaluation, there are 1 million history per cycle with 300 active and 100 inactive cycles to achieve a MTC standard deviation of about 0.6 pcm/K. Meanwhile, the fuel temperature coefficient (FTC) is quite typical at any condition, about -3 pcm/K and its associated uncertainty is about 0.18 pcm/K.

Table VII: Temperature coefficients of the ATOM core

Condition	MTC (pcm/K)	FTC (pcm/K)
HFP-BOC	-52.9±0.6	-2.32±0.18
HZP-BOC	-48.8±0.5	-3.06±0.18
CZP-BOC	2.9±0.6	-2.85±0.18
HFP-EOC	-62.3±0.6	-2.85±0.18
HZP-EOC	-59.3±0.5	-3.08±0.18
CZP-EOC	3.0±0.6	-2.75±0.18

Table VIII: Cold shutdown evaluation

Case (@ CZP)	BOC, no Xenon		EOC*, no Xenon	
	k_{eff}	Rod worth	k_{eff}	Rod worth
ARO	1.09962	-	1.11569	-
ARI	0.90563	19,480	0.91053	20,196
N-1(F4)	0.95206	14,094	0.98886	11,495
N-1(H2)	0.95301	13,990	0.98606	11,783

*Rod worth unit = pcm, *at 600 EFPD*

The evaluation of the cold shutdown margin is listed in Table VIII, in which one CEA is assumed to be stuck (N-1) at the CZP condition. It can be observed that the sub-criticality of the core is assured at the CZP condition with the proposed CR pattern. It should be noted that the evaluation is evaluated without xenon and the two worst N-1 cases are listed.

4. Conclusions and Future Works

In this paper, the application of TOP-based lattice and cylindrical CSBA in the two-batch ATOM core with the reduced fuel pellet is neutronically investigated. It is demonstrated that the targeted 2-year cycle length can be achieved with practical axial and radial power. The burnup reactivity swing is small enough to assure the SBF operation, while the discharge burnup is comparable to that of the typical PWR. In addition, the use of TOP lattice results in a sufficiently negative MTC, which guarantees the inherent safety of the core and reduces the temperature defect. Consequently, the sub-criticality of the core is guaranteed with a practical checker-board CR arrangement. It is concluded that the TOP concept is neutronically feasible for the PWR lattice with the reduced fuel rod.

The fuel reduction is quite significant in this TOP concept with a reduced fuel radius. Consequently, the power density is proportionally increased. Therefore, a multi-physics investigation including safety analysis is essential and will be done in the future study

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