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A Spectral Optimization Study of Fuel Assembly for Soluble-Boron-Free SMR

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1. Introduction

Water-cooled small modular reactors (SMRs) are an attractive nuclear power plant option because of economics, sitting flexibility, integrated and simplified design. For simplicity and enhanced safety, a soluble-boron-free (SBF) operation for SMRs is desirable. It is because the SBF system eliminates several drawbacks of soluble boron (SB), e.g. complication of chemical and volume control system, possibly positive moderator temperature coefficient (MTC), etc. Moreover, the SBF operation was demonstrated to be beneficial for passive frequency operation and power maneuvering as the coolant temperature variation is minimized with a highly negative MTC available in the SBF system [1, 2].

The SBF operation for SMRs has been successfully achieved in recent studies [3, 4] with innovative burnable absorber designs. However, the neutron economy is quite low with discharge burnup of <30 GWd/tU with single batch fuel management (FM) since FA design, particularly for SBF condition, has never been investigated and optimized yet. It is mainly because SMRs are currently utilizing standard 17x17 PWR fuel assembly (FA) that was optimized for three-batch FM with SB. As SMRs mostly accompany with single batch FM for a long cycle length, enhanced fuel utilization and improved inherent safety are essential. Hence, a spectral optimization study of FA for high-performance SBF SMRs is investigated in this paper.

To perform parametric study for the optimization of SMR FA, the continuous-energy Monte Carlo Serpent 2 code [5] is used with the nuclear library ENDF/B-VII.1 as the Serpent 2 is capable of simulating interaction physics without major approximations, providing accurate nuclide depletion as well as on-the-fly cross-sectional temperature treatment. The FA parametric study is investigated in terms of cycle length, temperature coefficients, pin peaking factor (PPF), and neutron spectrum with respect to hydrogen-to-uranium (H/U) number ratio. Moreover, the SBF SMR, named ATOM (autonomous transportable on-demand reactor module), is also analyzed with the optimal H/U obtained from the parametric study. The core performance are investigated in terms of cycle length, discharge burnup, radial power, and temperature coefficients.

2. Parametric Study on 17x17 Fuel Assembly

The parametric study for SBF SMR is performed on the 17x17 FA in which the critical physics parameter, H/U ratio, is adjusted to investigate the neutronic performance of the FA. The detailed dimensions and specifications of the reference 17x17 PWR FA are listed in Table I and Fig. 1 [6]. It is assumed that in this study pellet radius and FA gap are fixed as its thermal and mechanical performances are optimal under PWR conditions. The pin pitch is adjusted to obtain various H/U ratios. For FA calculation, 300 active and 100 inactive cycles are used with 100,000 histories per cycle, resulting in about 5.0 pcm uncertainty of infinite multiplication factor.

Table I: Reference 17x17 FA design parameter

Parameter	Value
Fuel lattice	17x17
No. fuel rod/ guide tube	264/ 25
Fuel /pellet radius	UO_2 / 0.40958 cm
Clad inner/outer radii	0.41873 cm/ 0.47600 cm
Reference pin pitch	1.26230 cm
Reference FA pitch	21.60382 cm
Reference H/U ratio	~4.0
Coolant/ fuel tempts.	575 K/ 900 K

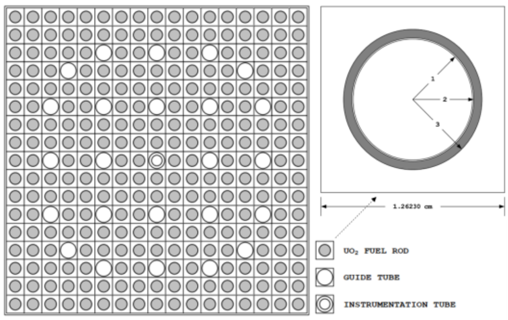

Fig. 1. 17x17 fuel assembly configuration

Fig. 2 shows the infinite multiplication factor with respect to the initial H/U ratio at 0 GWd/tU for different fuel enrichments and SB concentrations. One can that moderation capacity reduces with the presence of SB, while it enhances with a higher fuel enrichment. For 5.0 w/o UO_2, the optimal H/U ratio at fresh condition is about 9.0. It should be recalled that the maximum allowable enrichment is 5.0 w/o while the average fuel enrichment is about 4.5 w/o in commercial PWR due to fuel zoning. In addition, the highly under-moderated H/U ratio, about 4.0, in commercial PWR is mainly due to potentially positive MTC at CZP-BOC (the beginning of cycle) condition when boron concentration is high, about 2,150 ppm [7]. Furthermore, moderation capacity slightly enhances with burnup due to the depletion of fuel. It is clear that a higher H/U ratio can be applicable for SBF system and a higher fuel enrichment, within limitation, is preferable.

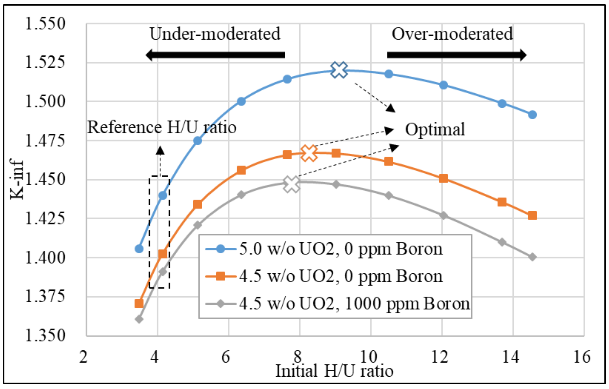

Fig. 2. The k_{inf} behavior with respect to H/U ratio.

The burnup-dependent infinite multiplication factor of non-poisonous 5w/o UO_2 FAs for various initial H/U ratios are depicted in Fig. 3. One can notice that the higher the initial H/U ratio is, the higher k_{inf} at BOC is. However, after a certain burnup, the behavior of k_{inf} is inversed. It is due to the depletion of the fuel, particularly U-235, and H/U ratio gradually increases and turns into over-moderated region.

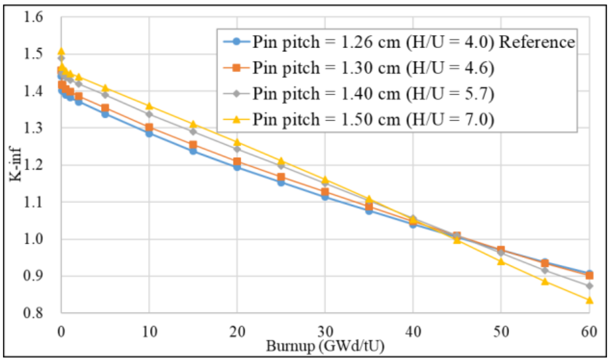

Fig. 3. The k_{inf} evolution for various initial H/U ratios

In order to investigate the cycle length and discharge burnup, a linear reactivity model is used with a neutron leakage assumption of about 7,000 pcm and a specific power density of 26.0 W/gU [8]. The enrichment of fuel is fixed as 5.0 w/o. The numerical results are listed in Table II corresponding to single and two-batch FMs. It can be seen that for both FMs, the cycle length and discharge burnup increase significantly with a slight increase in the initial H/U ratio from the reference one. They are maximum with 5.7 H/U ratio and then decrease dramatically with H/U ratio beyond 5.7. With optimal H/U, the cycle length can be enhanced about one month with single batch FM and discharge burnup enhancement is ~ 1.4 GWd/tU with two-batch one.

As aforementioned, a large amount of BA is required to load into SBF core to suppress major excess reactivity during the cycle. An amount of Gd for a successful SBF operation is about 2% the amount of fuel [9]. Moreover, the presence of strong absorbing materials, particularly Gd, has significant impacts on neutron spectral. Hence, a BA-loaded lattice calculation is performed for spectral optimization of SBF system.

Table II: Cycle length and discharge burnup for various initial H/U ratio and FMs

Initial H/U ratio	Pin pitch (cm)	Single Batch		Two-Batch	
		Discharge Burnup (GWd/tU)	Cycle Length (days)	Discharge Burnup (GWd/tU)	Cycle length (days)
4.0*	1.26	34.78	1,369	46.38	913
4.6	1.30	35.65	1,403	47.54	936
5.7	1.40	35.80	1,409	47.74	940
7.0	1.50	34.70	1,366	46.26	911

* *reference case*

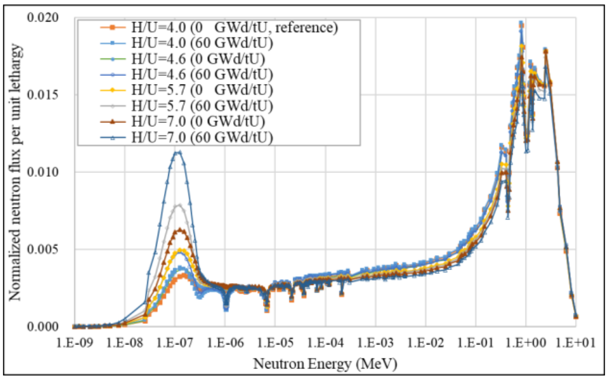

Fig. 4. Neutron spectrum with respect to various initial H/U ratio at 0 and 60 GWd/tU

The neutron spectrum comparison for two initial H/U ratios at 0 and 60 GWd/tU is shown in Fig. 4. One can be seen that the neutron spectrum becomes softened with increased H/U ratio. The significantly softened spectrum with a high H/U ratio, 7.0, indicates that the over moderation reduces noticeably cycle length and discharge burnup. In addition, the neutron spectrum at 60 GWd/tU is clearly softer than that at 0 GWd/U. It is mainly because Gd has a very strong thermal neutron absorption cross section and neutron moderation becomes more dominant at high burnup when Gd is largely burned out.

Impacts of initial H/U ratio on burnup-dependent PPF is presented in Fig. 5. One can notice that PPF is linearly decreasing with burnup for all cases and the maximum value is about 1.08 at the fresh condition. The PPFs FAs with larger H/U ratios are slightly smaller than that of the case regardless of burnup. It is because the impact of water-filled guide tube on PPF is less significant as the neutron spectrum are more softened with high H/R ratio, especially at high burnup condition. The associated uncertainty of the PPF is about 0.4%.

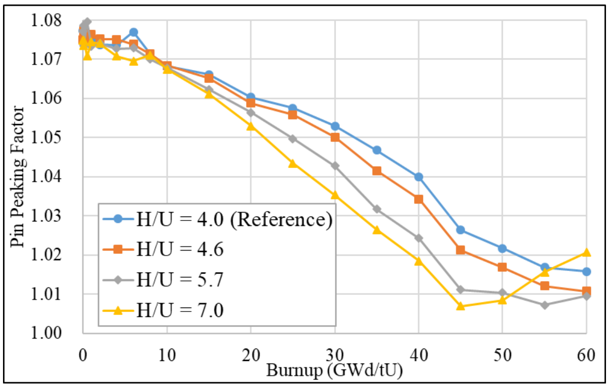

Fig. 5. Burnup-dependent PPF with respect to various H/U ratios

Table III: FTC and MTC (pcm/K) values respect to various initial H/U at 0 and 60 GWd/tU

Case	MTC @ 0 GWd/tU		MTC @ 60 GWd/tU	
	Wo/ BA	W/ BA	Wo/ BA	W/ BA
Ref.	-23.5	-33.4	-58.33	-61.7
H/U = 4.6	-22.2	-31.0	-50.16	-54.9
H/U = 5.7	-15.4	-23.9	-33.47	-36.9
H/U = 7.0	-8.60	-16.9	-16.8	-18.6
Case	FTC @ 0 GWd/tU		FTC @ 60 GWd/tU	
	Wo/ BA	W/ BA	Wo/ BA	W/ BA
Ref.	-1.91	-2.97	-3.75	-3.87
H/U = 4.6	-1.74	-2.79	-3.50	-3.64
H/U = 5.7	-1.52	-2.38	-2.95	-3.12
H/U = 7.0	-1.30	-2.04	-2.52	-2.66

One of the most important parameters for the inherent safety of the core and autonomous operation are FTC and MTC. However, highly negative FTC and MTC are not always preferable as a less negative FTC reduces the deviation of the inlet coolant during autonomous operation [2]. It is recommended that MTC should be smaller than -20.0 pcm/K and fuel temperature coefficient (FTC) should be about -2.0 pcm/K for a successful passive frequency operation. The FTC and MTC values with and without BA for various initial H/U ratios at full power condition are listed in Table III. One can notice that both FTC and MTC are less negative with increased H/U ratio due to the softening neutron spectrum, while they are more negative with increased burnup due to Pu buildup. According to ref. [2], the optimal H/U ratio for autonomous operation is around 5.7 as the FTC is about -2 pcm/K and the MTC is less than -20 pcm/K. The associated uncertainties of FTC and MTC are 0.14 pcm/K and 0.8 pcm/K, respectively. It is assumed that both FTC and MTC are linear functions of temperature in this evaluation.

On the other hand, temperature defect corresponding to various initial H/U ratios at 0 and 60 GWd/tU are tabulated in Table IV. As expected, the temperature defect decreases significantly as H/U ratio increases since both FTC and MTC are smaller with a higher H/U ratio as shown in Table III. It is advantageous that smaller shutdown rod worth is required for a larger H/U ratio. In addition, the control rod radius can be enlarged with a higher H/U ratio to enhance control rod worth. Temperature defect is the reactivity difference between HFP and CZP conditions. The associated uncertainty of temperature defect is about 12 pcm.

Table IV: Temperature defect with respect to initial H/U ratio and burnup for BA-loaded FA.

Case	@ 0 GWd/tU	@ 60 GWd/tU
Ref.	4,941 pcm	7,943 pcm
H/U = 4.6	4,490 pcm	7,045 pcm
H/U = 5.7	3,359 pcm	4,484 pcm
H/U = 7.0	2,302 pcm	1,833 pcm

3. The ATOM Core Analysis.

As demonstrated in the previous section, the slightly increased H/U ratio compared to the reference one enhances noticeably the cycle length while reducing the local peaking factor, and remaining the inherent safety features. In this section, the ATOM core is analyzed with quite optimal pin pitch, 1.35 cm (H/U = 5.2), and compared with the reference one. The selection of pin pitch of 1.35 cm is that it can offer more negative temperature coefficients, while the cycle length is almost maximum.

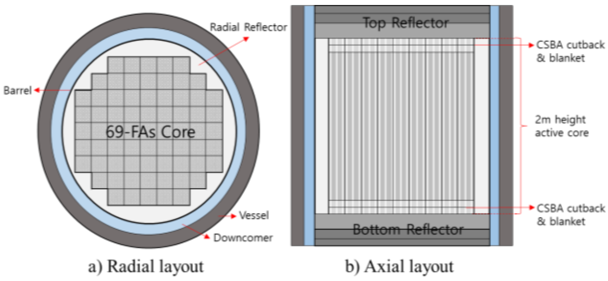

Fig. 6. The radial and axial ATOM core layouts

Table V: The ATOM core design parameters.

Parameters	Value
Thermal power	450 MWth
Fuel materials, enrichment	UO_2, 5.0 w/o
Radial reflectors	SS-304
BA design	DiBA
BA material	Gd
FA type, number of FA	17 x 17, 69
Reactivity swing (target)	1,000 pcm
Pin pitch (cm)	1.26 and 1.35

The ATOM core layouts and design parameters are shown in Fig. 6. and Table V. The core is to be designed to generate 450 MWth with a long cycle length. The active core comprises 69 17x17 (FAs) and each FA has 264 BA-loaded fuel rods with the standard UO_2 pellet, and 25 guide tubes. The fuel enrichment is 5.0 w/o with 95.5 % theoretical density. At both ends of the fuel rod, 5 cm 2.0 w/o UO_2 blankets and BA cutbacks are placed to minimize axial neutron leakage, peaking factor, and residual gadolinium. The target reactivity swing for SBF system is set to be about 1,000 pcm in the ATOM core.

To obtain a small reactivity swing in the ATOM core for SBF operation. The newly-proposed burnable absorber design, named DiBA (Disk-type burnable absorber), is utilized [10]. In the DiBA design, a thin cylindrical gadolinium disk clad with Zircaloy-4 is placed between fuel pellets for an extremely effective reactivity control. The spatial self-shielding effect of BA can be significantly enhanced as it is loaded into an interface between the pellets that have a strong spatial self-shielding regarding thermal neutrons. The conceptual design of the DiBA is shown in Fig. 7.

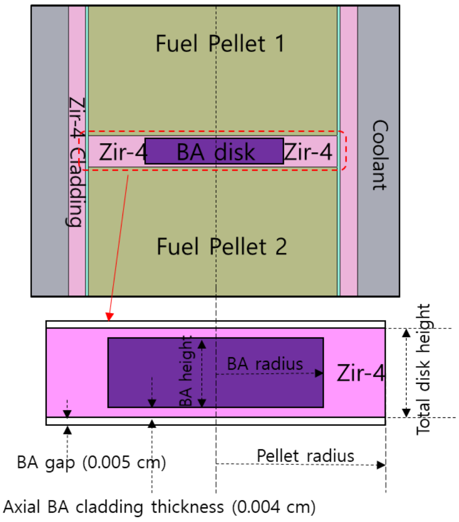

Fig. 7: The DiBA design.

There are three unique DiBA designs to minimize the burnup reactivity swing loaded into three regions. The BA loading pattern for the ATOM core is shown in Fig. 8 and Table VI. A larger volume BA design is loaded into the zone I in the inner core to reduce fuel depletion rates here and consequently to flatten radial power profile. Smaller volume BA designs are applied to zones II and III, respectively, as power density at these zones is lower than at zone I in general. In particular, the BA loading in the peripheral zone III is significantly smaller to minimize the residual Gd at the end of the core life.

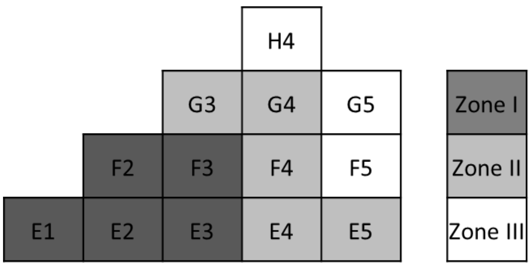

Fig. 8: The quarter-core DiBA Loading

Table VI: Zone-wise DiBA Loading Strategy.

Zone I		Zone II		Zone III	
BA vol. (cc)	D/H ratio	BA vol. (cc)	D/H ratio	BA vol. (cc)	D/H ratio
0.015	3.6	0.0125	3.6	0.005	7.9

D/H = diameter-to-height ratio

Figure 9 and Table VII show the neutronic performance of the DiBA-loaded cores with reference pin pitch and optimal one, P=1.35 cm, in comparison with the non-poisonous cases. It can be seen that without BA cases the average discharge burnup increases by about 2.5 GWd/tU, ~ 100 days in terms of cycle length, by increasing pin pitch from 1.26 cm to 1.35 cm. Meanwhile, the use of BA results in about 4.2 GWd/tU reduction between the cases with P=1.26 cm due to residual Gd reactivity. For the same BA loading pattern as shown in Table VI, the discharge burnup of the DiBA-loaded core with P=1.35 cm, 35.01 GWd/tU, is significantly higher than that with P=1.26 cm, 30.29 GWd/tU. However, its reactivity swing is about 4,200 pcm, almost four times higher than that with P=1.26 cm (~1,260 pcm). It is demonstrated that a larger amount of BA should be loaded to the core with P=1.35 cm for attaining the SBF operation. The fuel inventory is preserved in the DiBA-loaded cores by increasing active core height considering the accumulated height of DiBA.

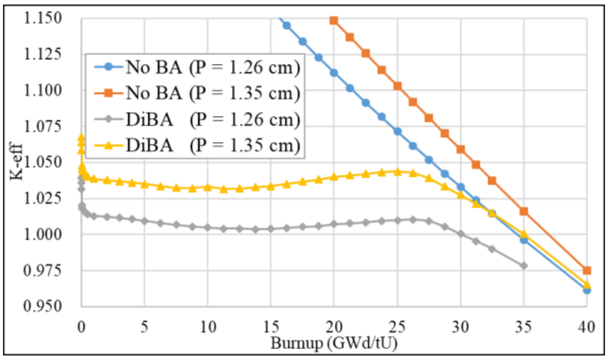

Fig. 9. Evolution of k_{eff} in various ATOM cores

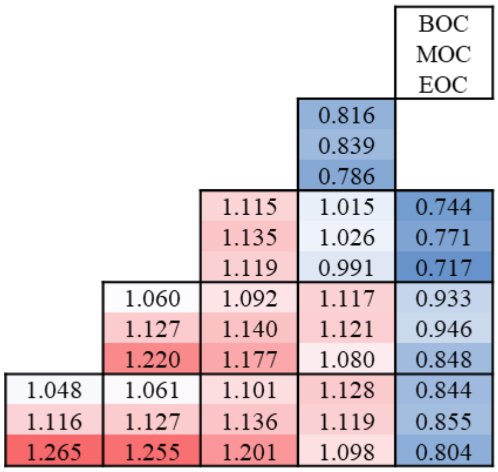

Fig. 10. Assembly-wise power distribution of the octant ATOM core.

Table VII: Neutronic performances of the ATOM cores

Case	ρ_{swing} (pcm)	Cycle Length (day)	Discharge Burnup (GWd/tU)	Core Height (cm)
No BA P=1.26 cm	-	1,358	34.51	200
No BA P= 1.35cm	-	1,456	36.98	200
DiBA P=1.26 cm	1,260	1,190	30.16	220
DiBA P=1.35 cm	4,193	1,383	35.01	220

$\rho_{swing} = (k_{eff}^{max}-1)/k_{eff}^{max}$ *at eq. xenon condition*

The radial power of the DiBA-loaded ATOM core is presented in Fig. 10. It can be seen that the radial power is clearly flattened over the cycle with a peaking factor of about 1.265 at EOC condition. It is demonstrated that the use of DiBA is superior in power flattening and reactivity suppression. The associated uncertainty of radial power is 0.2 %.

On the other hand, evaluations of FTC and MTC for the DiBA-loaded core are shown in Table VIII at BOC and EOC. The MTC at BOC and EOC are -36.0 and -46.3 pcm/K, respectively. Meanwhile, FTC values are between -1.96 and -2.45 pcm/K for the two conditions. One can notice that the whole-core FTC and MTC are slightly different for the lattice FTC and MTC, which is mainly due to the contribution of neutron leakage.

Table VIII: FTC and MTC of the DiBA-loaded ATOM core

Condition	MTC (pcm/K)	FTC (pcm/K)
BOC	-36.0 ± 0.65	-1.96 ±0.13
EOC	-46.3 ± 0.52	-2.45 ±0.10

The increased H/U ratio corresponds to an enhanced coolant fraction (larger pin pitch and FA pitch) in the core. For 1.35 cm, the FA pitch is 23.095 cm, resulting in an equivalent core diameter of 216.5 cm. Meanwhile, the equivalent core diameter corresponding to the reference pin pitch is 202.5 cm. On the other hand, the mass flow rate is reduced from 1,325 kg/m^2.s with P = 1.26 to 1,046 kg/m^2.s with P= 1.35 cm. In addition, the average coolant speed for P = 1.26 cm and 1.35 cm are 1.84 and 1.45 m/s, respectively. Consequently, pumping power and pressure drop are proportionally reduced for a given temperature rise of 35.7 K [9] with P=1.35 cm. Therefore, the natural circulation is significantly enhanced, which can improve the removal of decay heat during accidental scenarios and the passive safety.

4. Conclusions

The spectral parametric study of the fuel assembly for the SBF ATOM core is performed in this paper. The numerical results show that the cycle length and discharge burnup can be increased noticeably by increasing slightly hydrogen-to-uranium number density ratio. On top of that, the local peaking factor is marginally reduced with a larger H/U ratio at any burnup condition. In addition, the selected optimal FA design is adopted and analyzed in the ATOM core and compared to the reference case. It is demonstrated that the discharge burnup of the core with P=1.35 cm can be enhanced significantly, about 2.5 GWd/tU without BA case and 4.7 GWd/tU with BA case. Meanwhile, optimal temperature coefficients for the autonomous operation can be achieved while maintaining the inherent safety features. In addition, the use of DiBA are superior in minimizing excess reactivity and power peaking factor. All in all, the use of DiBA and slightly larger H/U ratio compared to those of current PWR are highly advantageous for SBF SMR.

Acknowledgement

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