Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

i-SMR Core Design Option Study with Gadolinium Nitride Coating Burnable Absorber

Woo Jin Lee, Sung Hyun Cho and Ser Gi Hong*
Departments of Nuclear Engineering, Hanyang University, 222, Wangsimni-ro, Seongdong-gu, Seoul, 04761, Republic of Korea
Corresponding author: hongsergi@hanyang.ac.kr

***Keywords :** Soluble Boron Free (SBF) core, GdN-CBA, multi-cycle, Control Rod*

1. Introduction

Soluble boron-free (SBF) operation enhances reactor safety by reducing liquid radioactive waste, eliminating corrosion issues caused by boric acid in the primary coolant system, and providing inherent safety through a more negative moderator temperature coefficient (MTC). However, SBF operation presents technical issues. First, excess reactivity has to be controlled only by control rods (CR) and burnable absorbers (BA) without soluble boron. Second, achieving The sub-criticality under CZP (Cold Zero Power) condition becomes more difficult to be achieved due to the more negative MTC.

Despite these challenges, numerous studies have showed the technical feasibility of SBF core designs. In light of these developments, this study aims to design a SBF core and assess neutronic feasibility. The selected core is i-SMR [1], which is currently under development in south Korea. This paper utilized Gadolinium Nitride Coating Burnable Absorbers (GdN-CBA), previously explored in [2, 3, 4, 5]. The i-SMR core considered Top-Mounted In-Core Instrumentation (TM-ICI) system to mitigate severe accident risks. To implement this system in the designed core, 20 TM-ICI positions were allocated, with the remaining 49 positions occupied by Control Element Assemblies (CEAs).

This study examines core sub-criticality under Hot Zero Power (HZP) and Cold Zero Power (CZP) conditions, analyzing core parameters such as power peaking factor and axial offset (AO) in multiple cycles through critical control rod position searches. A target cycle length is 730 EFPDs, and a two-batch fuel management scheme was adopted to increase both cycle length and discharge burnup.

2. Design and methodologies

2.1 GdN-CBA Design

Figure 1 shows the configuration of GdN-CBA. GdN-CBA is a coating-type burnable absorber that replaces the outer part of the UO_2 pellet with a GdN coating, thus preserving the fuel gap space and fuel rod dimensions as the conventional PWR fuel rods. The GdN-coating has higher thermal conductivity compared to Gadolinia and exhibits a similar thermal expansion coefficient as UO_2 pellet [6]. The neutronic performance of GdN-CBA was investigated in previous research [2,3,4,5]. It has been demonstrated that various combinations of coating thicknesses enable efficient reactivity control over a long cycle. However, using many types of coatings and thick coating layers can cause feasibility issues from manufacturing aspects. Therefore, it is crucial to carefully select both the type and thickness of coatings through a comprehensive analysis keeping minimal number of coating thicknesses for simplicity in manufacturing.

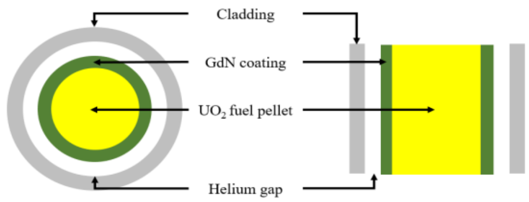

Fig. 1. Radial and axial configurations of GdN-CBA

2.2. Fuel Assembly and Core Design with GDN-CBA

Table I summarizes the design parameters of SBF core. The core consists of 69 17x17 Westinghouse type fuel assemblies (FAs) with active fuel height of 240cm. The core thermal power is $520MW_{th}$. To increase both cycle length and discharge burnup, a 2-batch fuel management scheme was adopted, with a target cycle length set to 730 EFPDs. The other feature of the SBF core is the use of a solid-type stainless steel-304 radial reflectors to reduce neutron leakage. The uranium enrichment in fuel pellets was adopted at less than 5% and considering simple manufacturing, only three thickness types of the GdN coating - 0.14mm, 0.35mm, and 0.6mm - were used. The last two columns of this table summarize the design constraints. Additionally, it must achieve subcriticality ($k_{eff} < 0.95$) under all-rods-in (ARI) condition at CZP [7].

The calculations for SBF core design were performed by the two-step procedure comprised of FA depletion and core calculations. FA depletion calculations were performed using the DeCART2D code developed by the Korea Atomic Energy Research Institute (KAERI) [8] while core depletion calculations were carried out using the MASTER code [9].

Table I: Design parameters of SBF core

Parameters	**Value**
Core	
Core thermal power	520 MW_{th}
Active core height	240 cm
Number of FAs	69
Average linear power density	118.9 W/cm
Fuel management scheme	2 batch
Radial reflector	Stainless steel 304
Core inlet temperature	295.5 ℃
Fuel assembly and fuel rod	
Assembly array	17x17 (Westinghouse type)
Fuel rod pitch	1.26 cm
Number of fuel rod per FA	264
Number of guide tubes per FA	25
Fuel pellet and GdN density	10.220 g/cm^3 8.645 g/cm^3
^{235}U enrichment	< 5.0 wt %
Thicknesses of GdN-CBA	0.14, 0.35, 0.6 mm
Design Target and constraints	
Cycle length	> 2 EFPYs
AO / Power peaking factor	-0.3 < AO < 0.3 Max F_q < 2.6 Max F_r < 1.7
k_{eff} under CZP condition	< 0.95

Fig. 2 shows evolution of the infinite multiplication factor (k_{inf}) for all designed FAs, calculated by DeCART2D, with the upper figure showing the results for the assemblies used in the first cycle and the lower one showing the ones for the assemblies used in the second to equilibrium cycles.

The 1st cycle incorporates four types of fresh FAs, designed with relatively flat k_{inf} profiles to ensure stable reactivity changes at the core scale. In contrast, five types of fresh FAs are introduced starting from the 2nd cycle, all utilizing 4.95 wt.% ^{235}U enrichment. Among these, A3, B3, and B6 are designed with increasing k_{inf} profiles to compensate for the reduced reactivity of depleted FAs from the previous cycle, facilitating in-out shuffling. Conversely, A4 and B4 FAs exhibit decreasing k_{inf} profiles, facilitating out-in shuffling.

Fig. 3 shows the examples of FA configurations used in the 1st cycle. These FAs utilize uranium enrichment below 4 wt.%. The FAs contain fuel rods with GdN coatings of different thicknesses, represented by the yellow-filled circles with colored outlines: 0.14 mm (red outline), 0.35 mm (green outline), and 0.60 mm (black outline). Some GdN-coated rods have cutback regions at the top and bottom, indicated by large red circles. The S1 and B2 FAs utilize Cutback 1, while the B1 and B5 FAs utilize Cutback 2. The 25 cm upper and 15 cm bottom (S1, B1) and 30cm upper and 15cm bottom (B2, B5) cutback regions do not include the GdN coating.

Another feature of the FAs is the longer axial burnable absorber (BA) cutbacks in the upper regions than the bottom cutbacks, designed to mitigate the downward power shifting in the SBF core.

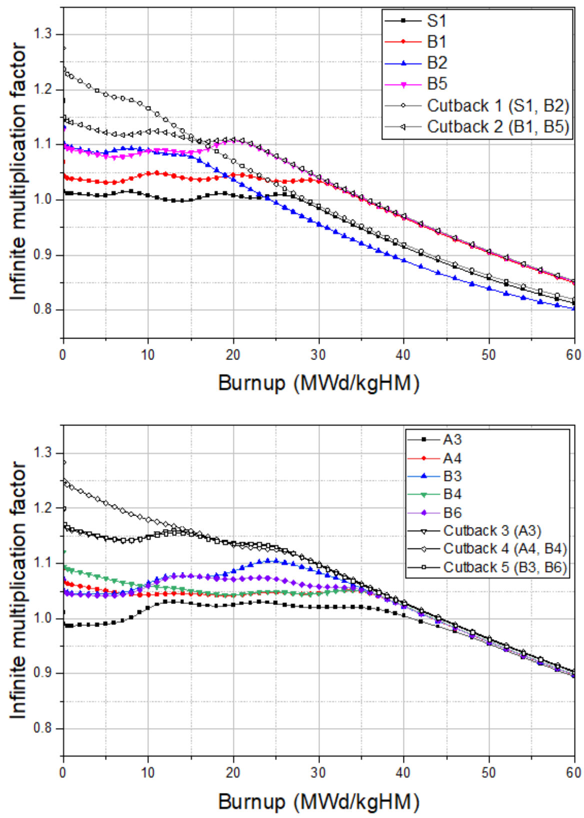

Fig. 2. Evolution of infinite multiplication factor (k_{inf}) with respect to designed FAs: 1st cycle (upper), 2nd to equilibrium cycle (lower)

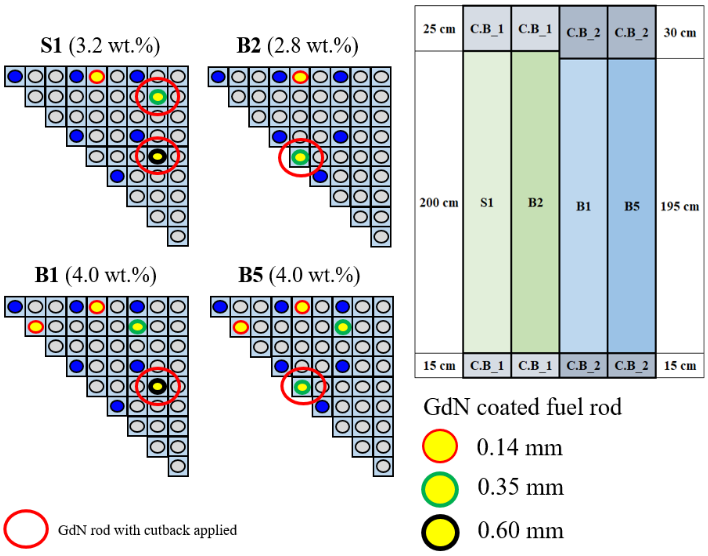

Fig. 3. Fuel assembly configuration of 1st cycle

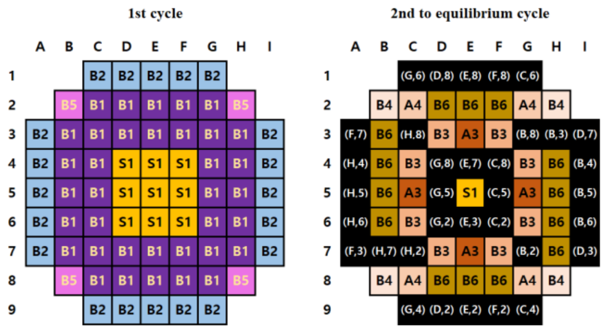

Fig. 4. SBF core loading pattern with 2-batch fuel management

Figure 4 illustrates the SBF core loading pattern utilizing a 2-batch fuel management scheme. The 1st cycle exhibits a symmetric pattern, while the subsequent cycles exhibit more complex patterns. After the 1st cycle, 35 fresh FAs are charged per cycle. Among these, the S1, comprising 3.2 wt.% enriched uranium pellets, is consistently discharged from the core center each cycle to facilitate the 2-batch design for the 69-FA core. This central placement of the S1 serves to mitigate the power peaking factor. The loading pattern incorporates a hybrid approach, combining in-out and out-in strategies. During shuffling, each FA is rotated to position its more depleted surface towards the opposite side, optimizing fuel utilization.

2.2 Control rod design

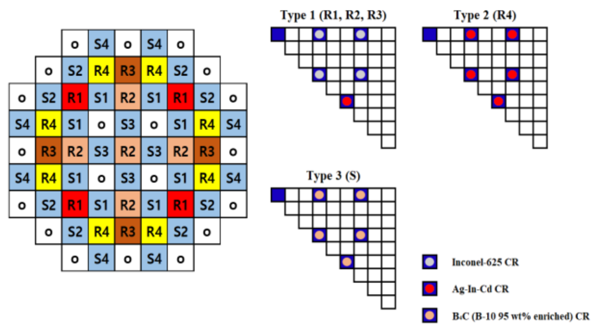

Fig. 5. Configuration of CEA design

Fig. 5 illustrates the loading pattern of CEAs. There are 49 CEAs, consisting of 21 regulating banks (R) to control reactivity during depletions and 28 shutdown banks (S) for reactor shutdowns. TM-ICIs are placed in the remaining 20 of the 69 positions. The R bank is divided into four groups: R1, R2, R3, and R4. Among these, groups R1, R2, and R3 are inserted during hot-full-power (HFP) operation of the SBF core. To mitigate power distribution distortions during CR operation, an absorber similar to the gray rod, is applied. The right side of Fig.5 shows the FAs with the control rod fully inserted. In the R1, R2, and R3 banks, 20 out of 24 fingers use Inconel-625, while the remaining 4 fingers use Ag-In-Cd (AIC) as neutron absorber material. Conversely, all 24 fingers in the R4 bank use AIC. To achieve sufficient subcriticality during CZP power with a limited number of CEAs, B_4C with 95 wt.% enriched B-10 is used in the shutdown bank.

A cladding material for the CRs is Inconel-625. The absorber pellet radius is 0.433 cm for the R bank, while a smaller radius of 0.408 cm is applied for the S bank to ensure sufficient gap space to alleviate the swelling of B_4C due to B-10 [10].

For the safety of the SBF core, it is necessary to secure sufficient shutdown margin. In addition, the limited number of CEAs must satisfy the subcriticality (N-1 k_{eff} < 0.99, ARI k_{eff} < 0.95) at CZP [7]. Table II summarizes the shutdown margin (SDM) and CZP subcriticality calculated from BOCs in cycles 1, 2, 3 and 8 cycles. SDM was calculated with a single CEA with the largest CR worth value being stuck, considering temperature, power defects from hot full power (HFP) to hot zero power (HZP), xenon and samarium defects, with an assumed uncertainty of 10% in calculations.

The calculation results for all considered the cycles are over 11,000 pcm, showing that sufficient shutdown margin was secured. Both the ARI and N-1 CZP conditions also satisfied the subcritical conditions.

Table II: The SDM and CZP subcriticality of SBF core

Cycle	SDM	ARI CZP k_{eff} (No Xe, Sm)	N-1 CZP k_{eff} (No Xe, Sm)
1	12,768	0.9306	0.9817
2	12,218	0.9217	0.9615
3	11,258	0.9366	0.9809
8	11,504	0.9337	0.9750

3. Numerical analysis and results

3.1 All-Rod-Out Results

Fig. 6 compares the evolutions of the excess reactivity from 1st cycle to 12th cycle, which were estimated without control rod insertion. Since fresh FA with uranium enrichement of 4.95 wt.% is loaded after the 1st cycle, the reactivity gradually increases from the 2nd cycle and then the maximum is achieved in 3rd cycle.

The maximum excess reactivities range 1915 pcm ~2581 pcm, depending on the cycles while the cycle lengths range 620 EFPDs ~ 880 EFPDs. Except for the second cycle, the cycle length met the target of over 2 EFPYs (730 EFPDs), converging to 800 EFPD after the 8th cycle.

Figure 7 shows the FA-wise burnup distribution in ARO state at the EOC of the 8th cycle. Among the once-burnt FAs, the maximum discharge burnup is about 51.4 MWd/kgHM and the minimum is 37.4 MWd/kgHM. The average discharge burnup is 40.245 MWd/kgHM.

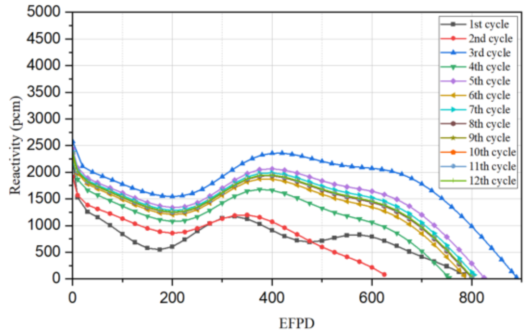

Fig. 6. Evolution of excess reactivity from 1st cycle to 12th cycle.

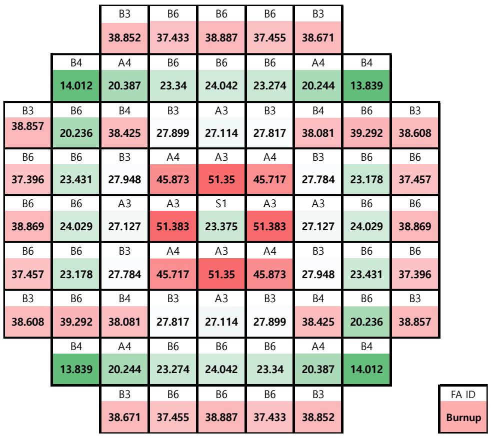

Fig. 7. FA-wise burnup distribution in ARO state at the EOC of 8th cycle

3.2 Control rod operation

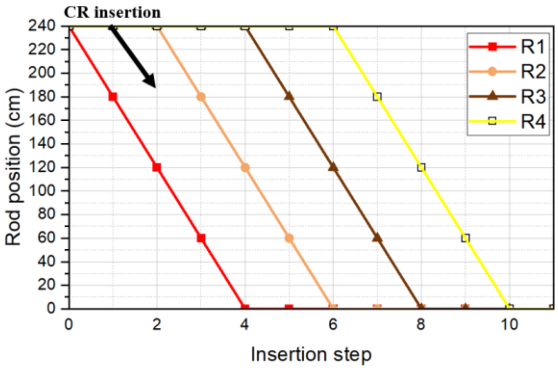

Fig. 8. Control rod insertion order and strategy

The core performance described in the section 3.1 is about ARO state. Therefore, the remaining excess reactivity should be controlled by the control rod in order to achieve SBF core operation. Fig. 8 shows the control rod insertion strategy. The control rods are inserted in the sequence of R1, R2, R3, and R4, with a 120 cm overlap to maintain uniform differential rod worth.

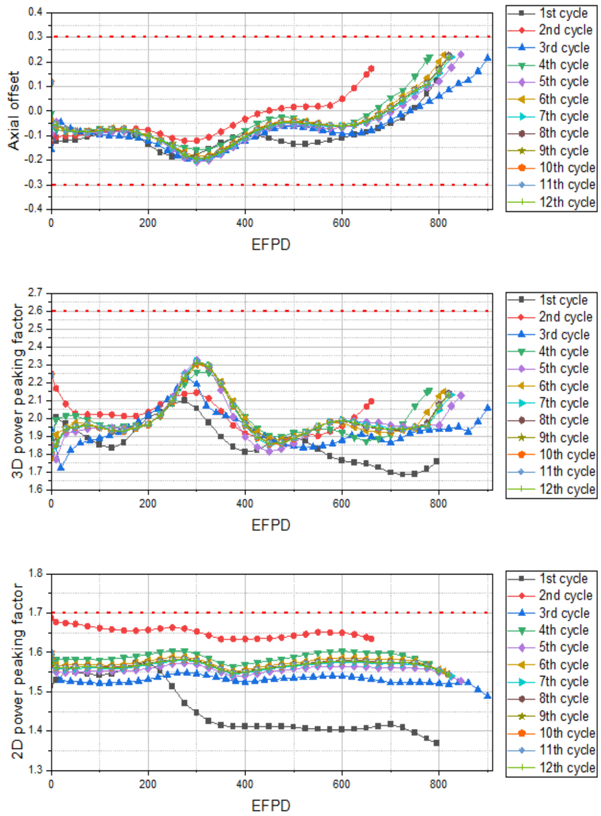

Fig. 9. Evolution of AO (top) and power peaking factors (middle and bottom) with respect to EFPD from 1st cycle to 12th cycle.

Fig. 9 illustrates the AO and power peaking factors (Fq and Fr) as a EFPD for cycles 1 through 12. The AO values remained within the target constraint of -0.3 to 0.3. As the cycles progressed towards EOC, a trend of increasing AO values was observed, correlating with the gradual withdrawal of control rods. The maximum absolute AO value was recorded in cycle 5, reaching a value of 0.23.

The total peaking factor (F_q) successfully also met its target constraint of 2.6 throughout the cycles. Similarly, the radial peaking factor (F_r) generally satisfied its target constraint of 1.7. However, it is noteworthy that F_r exhibited a peak value of 1.688 during the second cycle, approaching the constraint limit. This elevated F_r value can be attributed to the loading of fresh FAs with higher enrichment in the 2nd cycle. The introduction of these higher-enrichment FAs typically results in localized power peaks, particularly in their vicinity. Despite this peak in cycle 2, F_r values in the subsequent cycles remained well within the acceptable limits.

Fig. 10 shows the FA-wise burnup distribution with CR critical search at the EOC of 8th cycle. The average discharge burnup was 41.3 MWd/kgHM, an increase of about 1.1 MWd/kgHM compared to the ARO case. This is because the axial power distribution of the ARO case was extremely skewed upward, resulting in severe neutron leakage. Therefore, when control rods are inserted, the power distribution becomes relatively flat, resulting in an increase in cycle length and discharge burnup. The cycle length has reached 820 EFPDs, which is higher by 20 EFPDs than in the ARO case.

The data presented in Table III shows the successful optimization of the SBF core design over multiple cycles. The consistent EFPD values in later cycles, particularly from the 5th to 8th cycle, mean that the core design has achieved a stable equilibrium state. The AO values remain within an acceptable range. Both F_q and F_r values are maintained within safe operational limits across all cycles.

While further studies may be necessary for completed design, this study offers compelling support for the viability of the SBF core design, suggesting it can adequately address the challenges associated with SBF operation. For example, the second cycle is needed to be optimized to satisfy the design constraint in cycle length.

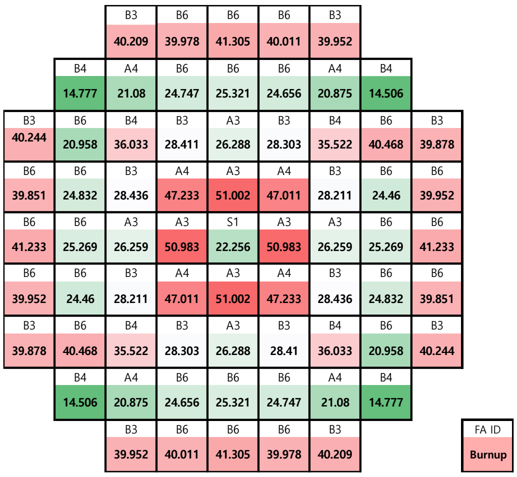

Fig. 10. FA-wise burnup distribution in CR inserted state at the EOC of 8th cycle

Table III: The summary of SBF core performance from 1st cycle to 8th cycle.

Cycle	EFPD	AO*	F_q*	F_r*	Avgerage discharge burnup (MWd/kgHM)
1	795	0.1883	2.100	1.574	18.19
2	660	0.1724	2.251	1.688	35.23
3	900	0.2142	2.225	1.565	39.39
4	780	0.2209	2.258	1.6046	41.95
5	845	0.2306	2.327	1.5746	40.82
6	810	0.2280	2.299	1.588	41.48
7	825	0.2198	2.321	1.579	41.06
8	820	0.2262	2.307	1.583	41.25

* Maximum value

4. Conclusions

This paper presents a neutronic design analysis of a SBF SMR core with a 520 MWth and 69 FAs. Considering efficient reactivity control and simple manufacturing, three types of GdN-CBA were used, and two batch fuel management was adopted to improve both cycle length and fuel burnup. The analysis demonstrates that the SBF core design successfully meets the design targets, with all cycles except the 2nd cycle achieving over 730 EFPD, while maintaining key safety parameters within acceptable limits. However, more studies are required to optimize the transient cycle cores to increase cycle length, reduce power peaking factors, and ensure the design maintains symmetry loading pattern throughout the operational cycles.

Acknowledgment

This work is financially supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Ministry of Trade, Industry and Energy (MOTIE) of Republic of Korea (No. RS-2024-00398867) and by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRS (RMAS) and the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 1500-1501-409).

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