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An innovative core design for a soluble-boron-free small pressurized water reactor

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Summary

This research investigates the neutronic feasibility of a high-performance soluble-boron-free (SBF) small modular reactor (SMR) core based on a new burnable absorber concept called the "Burnable Absorber-Integrated Guide Thimble" (BigT). Three unique BigT designs were loaded into the core; each BigT design was judiciously ascertained from the core radial power profile to tailor the required reactivity depletion patterns for an SBF operation. The approach is demonstrated to work well as the SBF SMR design exceeds the targeted cycle length while successfully controlling its burnup reactivity swing between 634 and 800 pcm throughout most of its operation. This paper also describes the use of hafnium-doped stainless steel as mechanical shim (MS) rods to attain the core criticality. Because the worth of the MS rods is relatively small, insertion and withdrawal of the rods during operation hardly alter the core radial power distributions. The resulting axial power profile, meanwhile, displays a more refined bottom-skewed pattern during the early portion of the irradiation cycle due to partial top-half insertion of the MS rods. This investigation further deliberates on a modified checker board control rod pattern to assure safe cold shutdown of the core. All calculations in this multiphysics assessment of the 3D SBF SMR core were completed by using a 2-step Monte Carlo deterministic hybrid procedure based on the Monte Carlo Serpent and COREDAX diffusion codes with the ENDF/B-7.1 nuclear data library.

KEYWORDS

BigT, boron-free, PWR, SMR

1 | INTRODUCTION

Dissolving boric acid in a primary coolant is one of the standard reactivity control measures in commercial pressurized water reactors (PWRs).[1] While this approach offers a desirably homogeneous reactivity control, it takes a relatively long time to adjust the boron concentration in the pressurized coolant when a quick response is needed. In addition, despite its widespread use, diluting soluble boron in the primary coolant is actually quite troublesome.[2-6] This is because boron makes the primary coolant slightly acidic and is therefore corrosive. To re-equilibrate its pH, lithium hydroxide is typically added to the coolant. Neutron activation reactions with the soluble boron and lithium isotopes result in 90% of total tritium generation in the primary coolant.[7] Furthermore, the critical boron concentration in the core is characteristically very high at the beginning of cycle (BOC) and progressively diluted toward 0 at the end of cycle (EOC). This deboration operation requires extensive

NOMENCLATURE: BA, burnable absorber; BigT, Burnable Absorber-Integrated Guide Thimble; BOC, beginning of cycle; BRS, burnup reactivity swing; EOC, end of cycle; MS, mechanical shim; MTC, moderator temperature coefficient; PWR, pressurized water reactor; SBF, soluble-boron-free; SMR, small modular reactor piping and circuitry networks, which complicate plant operation and maintenance. A very high critical boron concentration at the BOC can possibly cause the core moderator temperature coefficient (MTC) to be slightly positive, a clearly unfavorable safety feature of a PWR.[8] Therefore, eliminating soluble boron is an attractive possibility for safety and economy for the next generation of PWR core designs.

The pursuit for a soluble-boron-free (SBF) PWR core is actually not new as research on the subject was first archived in 1986.[2] Since then, a number of similar studies have been conducted on different configurations of the PWR core designs.[3,4,9,10] They all reached the same conclusions: (i) An alternative reactivity control system must be precisely defined and (ii) the SBF operation is technically feasible and less restrictive for a small PWR core. These conclusions were demonstrated in a catalog of SBF small modular reactor (SMR) paper designs.[11-18] Nevertheless, as of today, there is still no successful commercial SBF PWR core design.

This research assesses the neutronic feasibility of a new high-performance SBF SMR core. This research specifically pursues the SBF operation with control rods and an alternative reactivity control mechanism. Borated water injection system is maintained as the mandatory secondary independent emergency trip for safe cold shutdown assurance. For successful SBF PWR operation, the core burnup reactivity swing (BRS) must be sufficiently small (eg, <1000 pcm[3]) so that the use of mechanical shims (MSs) can be minimized. By limiting the use of MSs and control rods, their corresponding local power perturbations can thereby be curbed, which consequently enables practically acceptable power distributions in the core. In addition, the rod worth requirement can also be lowered so that the number of MSs and control rods can be maintained or even reduced in the SBF SMR core.

The SBF SMR core should be designed to survive a sudden power drop during a big transient. This is because when reactor power is suddenly reduced from an equilibrium xenon state in PWRs, some amount of positive reactivity should be made available to overcome negative reactivity resulting from the xenon buildup. Generally, about 600 pcm is required to survive a 100% to 20% power drop in a large modern PWR core, which is quite demanding. In other words, a minimum of ~600 pcm excess reactivity should always be maintained throughout the SBF operation. Of course, the reactor does not need to withstand such a big transient near the EOC because the actual excess reactivity can be smaller than 600 pcm. For a small PWR core, the value can be smaller. This is because the relatively lower power density in the smaller PWR core yields slower fissile consumption and thereby a lower flux level. Because the xenon level in a PWR core is flux-dependent, its equilibrium worth will thus be correspondingly smaller in a small PWR core. In this study, our goal was to maintain a BRS of about 400 to 500 pcm for the SMR core.

2 | THE BigT BURNABLE ABSORBER

State-of-the-art PWR burnable absorbers (BAs) have been shown to reliably help control the core reactivity. However, commercial BA designs come with characteristic drawbacks: For example, the integral absorber is not removable, the thimble-occupying discrete absorber prevents insertion of control rod, and the rod-displacing discrete absorber lowers the fissile inventory in the assembly.[19] In addition, most concepts are generally designed to be used in the first irradiation cycle of the fresh fuel assembly (FA) only, which limits their applications in the core. It is upon these observations that a new BA design is being pursued, one that potentially offers solutions not currently viable with the existing technologies, especially in enabling a high-performance SBF PWR core operation.

This research proposes a novel BA concept for the PWR called the "Burnable Absorber-Integrated Guide Thimble" (BigT).[20] Aptly named, the BigT absorber integrates BA materials into the standard guide thimble in a PWR FA. Even though the BigT actually comes in 3 distinct design concepts, this research focuses only on the BigT fixed azimuthally heterogeneous ring variant as shown in Figure 1. Burnable Absorber-Integrated Guide Thimble fixed azimuthally heterogeneous ring is essentially a modified PWR guide thimble containing 4 azimuthally heterogeneous BA pads embedded in its thimble ring. In normal configuration, all 24 guide thimbles in a representative 17 × 17 FA can be modified into the BigT, also as illustrated in Figure 1. The BigT, which can be easily and readily retrofitted into a commercial PWR, is neutronically very flexible by virtue of its BA spatial self-shielding variation (ie, the thickness and azimuthal span of the BA pads) so as to attain any desired reactivity depletion pattern. The BigT also allows full insertion of control rods in its thimble. These advantages may help realize any core management objective of the PWR, such as those of the initial core, low boron, and SBF core designs.[21-23]

3 | CALCULATION TOOLS

Preliminary investigation[23] clearly shows that the MTC in an SBF PWR core is strongly negative, suggesting that the core could be sensitive to the moderator temperature and density fluctuations. As such, a multiphysics calculation that couples neutronics and thermal-hydraulic feedback is necessary for the performance assessment of any SBF PWR core. It is upon this observation that a hybrid 2-step Monte Carlo deterministic reactor core analysis procedure was adopted in this

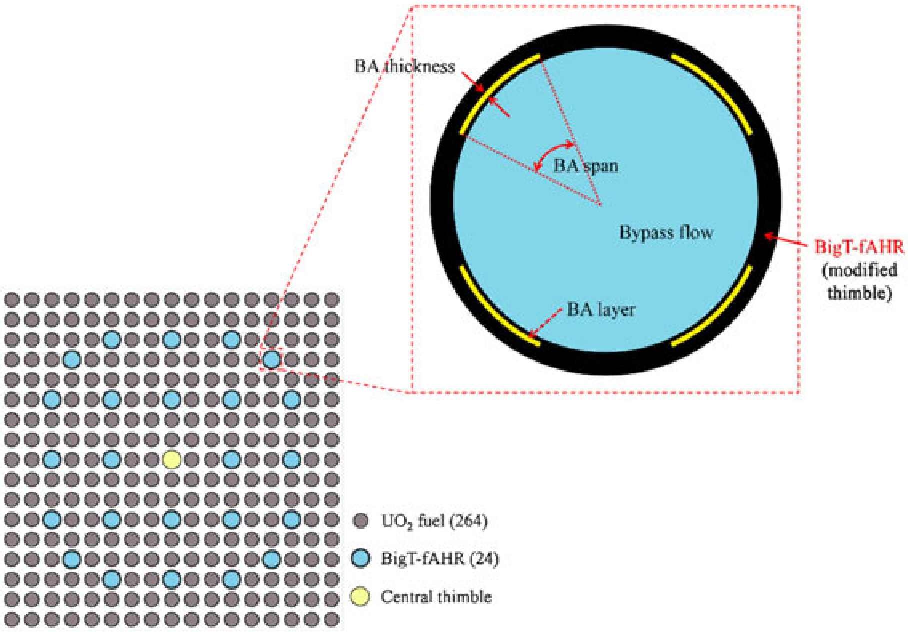

FIGURE 1 Representative layout of a Burnable Absorber-Integrated Guide Thimble (BigT)-loaded 17 × 17 fuel assembly [Colour figure can be viewed at wileyonlinelibrary.com]

research. In this work, the Monte Carlo Serpent[24] code was used for the FA spatial homogenization and the Korea Advanced Institute of Science and Technology-developed COREDAX[25] nodal diffusion code was used during the subsequent 3D nodal diffusion calculations.

The use of the continuous-energy Monte Carlo Serpent code for assembly spatial homogenization is very advantageous. This is because the Monte Carlo code is inherently capable of handling geometry models and interaction physics without major approximations. We can thus model heterogeneous lattice full-scale quite accurately, thus obtaining the best available reference solution for the problem. The capability of producing high quality reference results becomes particularly valuable in the modeling of novel reactor concepts, such as that of the BigT or any other system where experimental data are scarce or not available. Serpent comes with an integrated and accurate nuclide depletion module as well as on-the-fly cross-sectional temperature treatment, which are desirable features for an efficient lattice branch depletion calculation.

Meanwhile, COREDAX offers coupled neutronic and thermal-hydraulic calculation, which is essential in the SBF PWR core analysis. COREDAX code has been well validated against nuclear regulator-approved codes (eg, United States Nuclear Regulatory Commission's Purdue Advanced Reactor Core Simulator) in a number of benchmark problems.[25] A wrapper script was recently developed to link the Monte Carlo Serpent branch calculations to the 3D COREDAX nodal diffusion analysis.[26] The FORTRAN-based program extracts outputs from Serpent single assembly branch calculations and processes and organizes them into a COREDAX-formatted cross section database.

4 | NUMERICAL ANALYSIS AND RESULTS

4.1 | Small modular reactor core specification

The SMR core investigated in this study was based on 200 MWth small modular PWR design as described in Table 1.[27] A typical 17 × 17 FA was used as the FA. The active and whole core equivalent radii were 73.80 and 141 cm, respectively. The thickness of both the downcomer and reactor vessel was 20 cm. To improve its neutron

TABLE 1 Specifications of the small modular reactor (SMR) core[27]

Parameters	Value	Unit
Thermal power	200	MWth
Power density	58.4	kW/L
Fuel loading	Single batch	
Fuel assembly (FA) type	17 × 17	
Fuel materials	UO_2	
Fuel enrichment	4.9	w/o
Number of FAs	37	
Active core height	200	cm
[a]Burnup reactivity swing	<1000	pcm
Coolant inlet temperature	558.2	K
Coolant exit temperature	588.4	K

[a]((max k_{eff} − 1)/max k_{eff}) × 10^5 [pcm], target with equilibrium Xe.

economy in the compact PWR core, the core utilized steel reflector assemblies instead of the typical baffle-water design. This helped reduce radial neutron leakage quite significantly. To further minimize neutron leakage, we also adopted top (10 cm) and bottom (5 cm) axial fuel blankets for the core in the form of 2.0 w/o UO_2 fuels.

4.2 | Small modular reactor core design

Three unique BigT designs, which were placed in all 24 guide thimbles in the 17 × 17 FA (Figure 1). were loaded into the core region as shown in Figure 2. About 15 cm of BigT cutback was allocated to comply with the dashpot-compliant requirement of the standard 17 × 17 FA design. Detailed dimensions of the BigT absorbers are tabulated in Table 2. The value in parentheses of the first column in Table 2 denotes the number of fuel assemblies (of a total of 37) loaded with the respective BigT designs. In this study, we specifically selected 90 w/o enriched $^{10}B\ B_4C$ as BA material in the BigT to reduce the thickness, thus possibly extending the core cycle length due to the increased effective spatial self-shielding of the enriched B_4C.

Figure 2 also depicts the control absorber layout proposed for the BigT-loaded SMR core, with MS and shutdown bank rods arranged in a modified checker board pattern. There are 12 MS rods and a shutdown bank composed of 21 control rods and 1 leading regulating bank with 4 control rods. The MS-rodded assemblies are sorted into 4 groups to possibly minimize the required vessel head penetration and thus simplify the control rod operation. All MS rods are nonetheless to be operated together in steps of 1 to 2 cm. For the MS rod, 1.85 w/o hafnium-doped stainless steel is utilized as it suits our purpose very well: high density, mechanically stable, high thermal integrity, relatively long depletion lifespan, and weakly noticeable neutron absorption. Meanwhile, 95 w/o enriched $^{10}B\ B_4C$ (of radius 0.4041 cm) with Inconel cladding is the material of choice for the shutdown and regulating banks. The high enrichment of the B_4C assures a correspondingly high worth of the shutdown bank rods.

TABLE 2 Region-wise Burnable Absorber-Integrated Guide Thimble (BigT) designs in the soluble-boron-free (SBF) small modular reactor (SMR) core

Region (# of Fuel Assemblies, FAs)	Thick (mm)	Span (deg)
FA-1 (9)	0.090	70
FA-2 (12)	0.089	55
FA-3 (16)	0.019	60

Figure 3 shows burnup-dependent k_∞ depletion trends of the BigT-loaded FA tabulated in Table 3. The k_∞ trends were intentionally chosen to be relatively flat and smooth (by judiciously adjusting spatial self-shielding of the BigT), from the core center (assembly of position "D-4" in Figure 2) toward the core periphery (assembly of position E6 in Figure 2). In fact, reactivity suppressions in the core interior ring were extremely high, such that their k_∞ were very close to 1.0 (critical condition) throughout the assembly lifetime. This is because the power density in the interior assemblies was expected to be significantly higher than those in the core periphery.[27] Note that the k_∞ of the nonpoisonous assembly at 0 GWd/t is 1.42, indicating that BigT in FA-3 (which is the lightest loaded B_4C among the 3 BigT designs) suppresses about 20,900 pcm worth of reactivity at the BOC. Full reactivity depletion curve of the nonpoisonous assembly is, however, not shown in Figure 3 because its slope is relatively linear and not as dynamically interesting as the BigT-loaded assemblies.

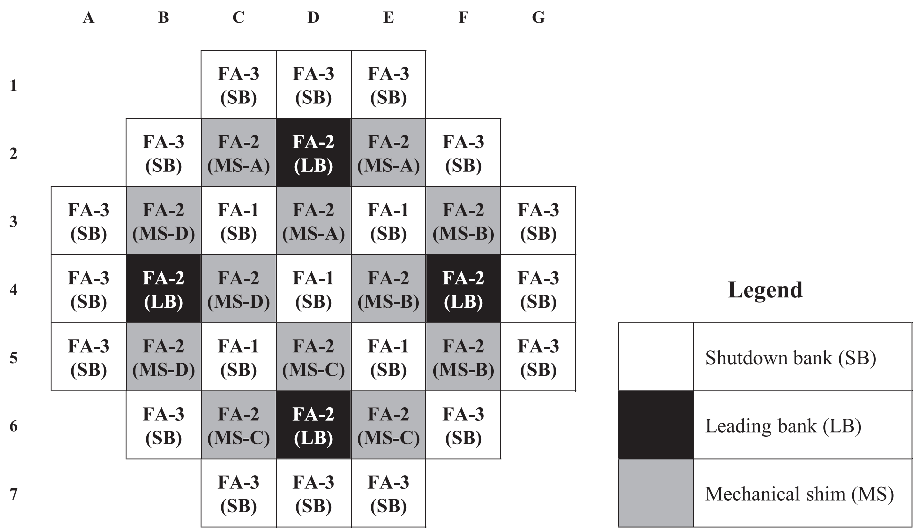

FIGURE 2 Burnable Absorber-Integrated Guide Thimble (BigT) loading, mechanical shim, and control rod pattern of the small modular reactor core

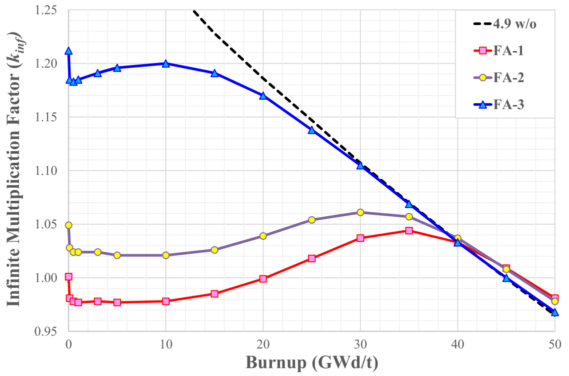

FIGURE 3 Burnup-dependent k_∞ of the Burnable Absorber-Integrated Guide Thimble (BigT)-loaded fuel assemblies [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Nodal burnup distributions of the mechanical shim (MS)-rodded soluble-boron-free (SBF) small modular reactor (SMR) at the end of cycle (EOC)

Axial Position (cm)	D4	D5	E5	D6	E6	F6	D7	E7
197.5	13.0	12.1	12.8	11.1	10.9	8.7	9.6	8.1
190.0	18.3	16.7	18.2	17.2	15.8	13.6	15.3	12.9
176.5	17.4	16.9	17.9	19.5	17.6	17.3	19.8	16.8
159.5	20.3	20.0	21.4	24.2	21.8	21.9	25.2	21.4
142.5	24.1	23.9	25.5	28.9	25.9	25.8	29.6	25.3
125.5	28.5	28.1	30.0	33.6	30.1	29.3	33.3	28.6
108.5	33.2	32.8	34.5	37.9	34.3	32.5	36.4	31.3
91.5	37.3	37.4	38.4	41.5	38.3	35.0	38.7	33.4
74.5	39.7	39.9	40.7	43.5	40.4	36.3	40.0	34.5
57.5	39.7	40.0	40.6	43.4	40.4	36.0	39.7	34.2
40.5	37.0	37.2	37.7	40.4	37.5	33.6	37.1	31.8
23.5	31.9	31.8	32.1	34.1	31.5	27.8	31.0	26.2
12.5	32.1	31.4	31.9	32.2	29.4	23.6	26.2	22.0
5.0	20.0	19.4	19.7	19.5	17.6	13.3	14.8	12.3
Average	29.3	29.1	30.1	32.4	29.7	27.3	30.5	26.1

4.3 | Characteristics of the soluble-boron-free core

Figure 4 depicts the burnup-dependent k_{eff} trend of the BigT-loaded SMR core against the reference core without any BAs. It is clear that very high reactivity (~20,000 pcm) is suppressed at the clean BOC in the BigT-loaded design, as k_{eff} hovers just above 1.0 and stays relatively flat throughout the whole irradiation cycle. The BigT-loaded SMR core, however, dips into the subcritical domain a bit earlier (30 GWd/t) than the nonpoisonous configuration (31.5 GWd/t), indicating that some B_4C in the BigT may have not been completely depleted at the EOC. On the global scale, the k_{eff} trend obtained in the BigT-loaded SMR core is very favorable.

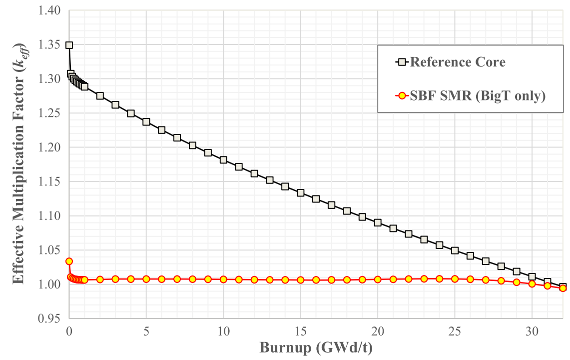

FIGURE 4 Burnup-dependent k_{eff} trends of the Burnable Absorber-Integrated Guide Thimble (BigT)-loaded against the reference core [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 5 zooms in the k_{eff} trend of the BigT-loaded SMR core. The core BRS is clearly less than 1000 pcm as is desirable for a successful SBF operation. It is also clear that the BigT-loaded core only encroaches on the subcriticality domain at 30 GWd/t (~53.6 effective full power months). Taking into account a single-batch fuel management in the current SMR design, the achieved cycle length and fuel burnup are considered to be rather high performance.

Figure 5 clearly shows that the core reactivity stays between 634 and 800 pcm throughout most of the simulated cycle, indicating that the core has sufficient excess reactivity to survive a sudden power drop in a big transient. This is because the transient xenon worth in such a sudden power drop is actually rather limited (~310 pcm as shown in Figure 6). Figure 10 was generated by using the 3D Monte Carlo Serpent calculations with stochastic uncertainties of the integral k_{eff} value less than 10 pcm. In addition, the transient xenon worth is actually substantially compensated for by the power decrease itself; ie, temperature feedbacks from both the fuel and the coolant provide some amount of positive reactivity because the MTC is strongly negative (−50 to −60 pcm/K) and the fuel temperature coefficient is also clearly negative (−2 to −3 pcm/K). As such, the

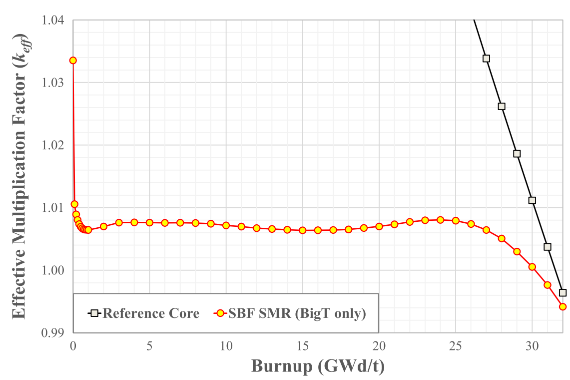

FIGURE 5 Burnup-dependent k_{eff} trend of the soluble-boron-free small modular reactor core [Colour figure can be viewed at wileyonlinelibrary.com]

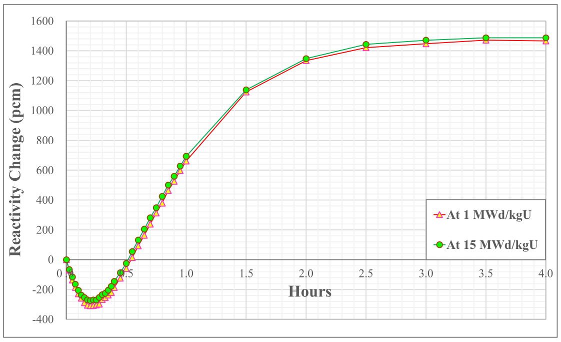

FIGURE 6 Transient reactivity change of the soluble-boron-free small modular reactor core after 100 to 15% power drop [Colour figure can be viewed at wileyonlinelibrary.com]

temperature feedback itself can at least be several hundred pcm. This indicates that even smaller excess reactivity (eg, 300-500 pcm) can still be acceptable in the SBF SMR operation.

4.4 | Criticality attainment during operation

The BigT-loaded SMR core presented in the previous subsection clearly meets the criteria for a successful SBF operation. It has, however, became obvious that a more complete solution is necessary at this point of the research, ie, one that attains criticality throughout the intended irradiation cycle. This study thereby aims to deliberate one such supplementary reactivity control mechanism, namely, in the use of a MS rod to attain criticality in the BigT-loaded SMR core configuration.

The required reactivity worth of the MS rods should clearly be about 600 pcm because the BRS in the BigT-loaded SBF core stays between 634 and 800 pcm throughout the cycle (Figure 9). In addition, the MS shim rods should also be symmetrically inserted in bulk throughout the core so that the resulting radial power perturbation can be minimized. It would also be advantageous if the MS rods were loaded mostly in the interior and middle ring because the core radial power actually peaks in these regions. In fact, additional reactivity suppression in these regions may actually help to make the radial power distribution more uniform. These MS rods must also stay away from the assemblies reserved for the shutdown bank insertion. Furthermore, the MS rods shall reside inside the BigT thimble throughout most of the core operational cycle (~52 months). As such, highly neutron-absorbing materials with a short depletion lifespan (eg, conventional Ag-In-Cd composition) would not be suitable as the MS rod in the SBF SMR design.

One must also note that the MS rod in the BigT thimble should be slightly smaller (0.4549 cm radius) than the conventional control rod (0.4839 cm radius). For the sake of the discussion, it is assumed that all assemblies in the core can be rodded. Strictly speaking, this may be impractical because control rods are typically checker-boarded in a conventional commercial PWR core, which results in insertion of control rods in about 50% of the total assemblies in the core. However, work has been ongoing to increase the number of rodded assemblies in a small integrated PWR core up to 100% by introducing a compact control rod driving mechanism.[16] It is thus assumed that this innovative mechanism can possibly be implemented in our BigT-loaded SMR core.

The MS and control rods are arranged in a modified checker board pattern as depicted in Figure 2. The results of the simulated core are described subsequently. Figure 7 depicts the core criticality search with gradual MS rod withdrawal throughout the operation. The secondary axis denotes the amount of MS rod withdrawal (from full insertion at BOC) required to attain the core criticality. Note that the MS rod covers the top half of the core throughout most of the SBF operation.

Figure 8 depicts the radial power distribution in the BigT-loaded and MS-rodded SMR core configuration at different burnups. As expected, the MS rod operation only slightly perturbs the radial power distribution in the core. This is because the worth of each individual MS rod is relatively small and they are distributed uniformly throughout the core radial layout.

Figures 9 and 10 show the axial power and core-average temperature distribution in the BigT-loaded and MS-rodded SMR core at different burnup conditions. As expected, the core is rather bottom-skewed at BOC and MOC due to the partial insertion of MS rods in the top half of the core. The core progressively becomes top-skewed with burnup as the MS rods are gradually removed from the core. There are clearly 2 local peaks at the BOC that denote the axial power transitions from the nonpoisonous cutback regions (zero reactivity suppression) to the BigT-loaded axial stacks (very heavy reactivity suppression). Note that the core-averaged fuel temperature closely follows the pattern of the core axial power profile as expected.

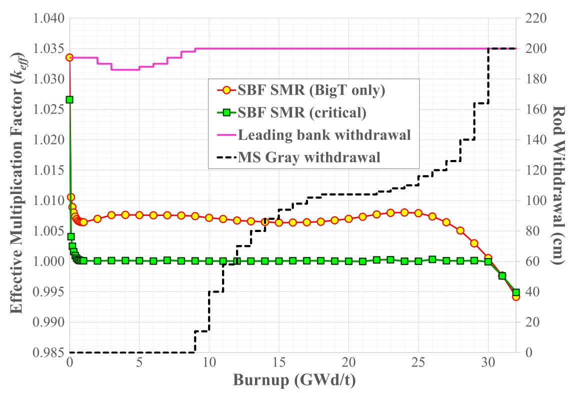

FIGURE 7 Core criticality attainment with gradual MS rod withdrawal [Colour figure can be viewed at wileyonlinelibrary.com]

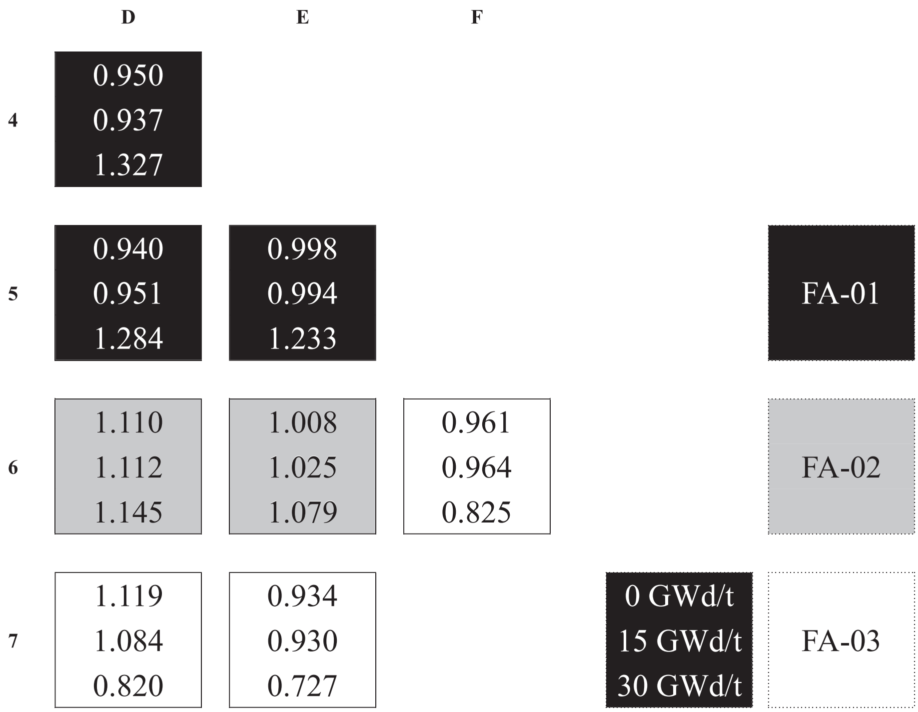

FIGURE 8 Radial power profile of the Burnable Absorber-Integrated Guide Thimble (BigT)-loaded small modular reactor core

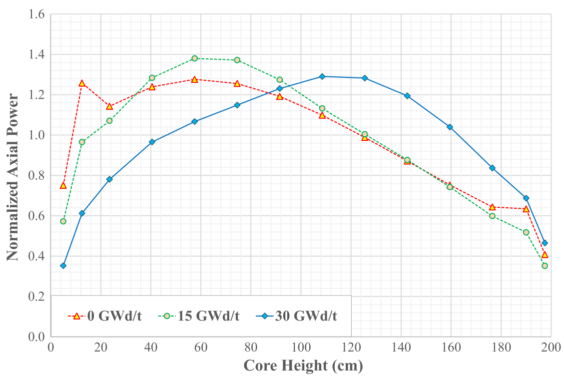

FIGURE 9 Axial power distribution of the Burnable Absorber-Integrated Guide Thimble (BigT)-loaded small modular reactor core [Colour figure can be viewed at wileyonlinelibrary.com]

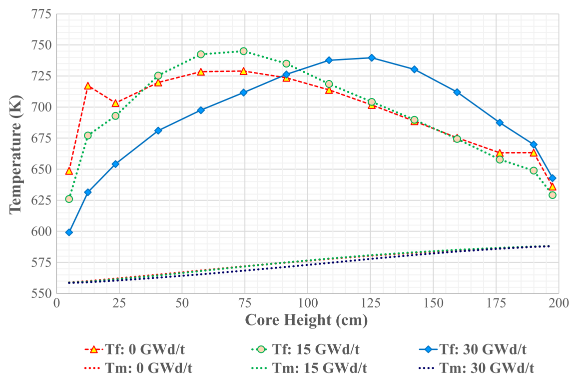

FIGURE 10 Core-averaged axial temperature distribution of the Burnable Absorber-Integrated Guide Thimble (BigT)-loaded small modular reactor core. (Tf = fuel temperature, Tm = coolant temperature) [Colour figure can be viewed at wileyonlinelibrary.com]

Table 3 compiles the nodal burnup distributions of the SBF SMR core at the EOC. Note that the values in the table are color-coded to scale (blueish is low burnup, while reddish is high burnup). One can see that there is higher burnup at the bottom half of the core due to the partial MS rod insertion in the top half of the core for most of the irradiation cycle. Nonetheless, the burnup distribution in the core is still reasonably practical.

To better appreciate the significance of Table 3, one should refer to k_∞ trends of the BigT-loaded fuel assemblies shown in Figure 10. When plotted against the reference nonpoisonous assembly (4.9 w/o UO_2 fuels), it is clear that B_4C in the BigTs are only completely depleted beyond 40 GWd/t. As such, there is some poisonous residual in the assemblies at 30 GWd/t (which is the average discharge burnup of most nodes shown in Table 3). This succinctly explains the 3 month shorter cycle length obtained in the BigT-loaded core as opposed to the non-poisonous core. As such, there is substantial room for optimization of the discharge burnup via node-wise BigT designs, if necessary. Nonetheless, the BigT loading strategy should be kept as simple as technically possible. As such, the current BigT-loaded SMR design is reasonably practical.

4.5 | Cold shutdown assurance

Table 4 tabulates the k_{eff} values of the SMR core at a clean BOC by using the Monte Carlo Serpent code. Statistical

TABLE 4 Beginning of cycle (BOC) clean core reactivity at hot zero power (HZP) and cold zero power (CZP) conditions

BOC, No Xenon	HZP (by Serpent, SD < 5 pcm)	CZP (by Serpent, SD < 5 pcm)	CZP (by COREDAX)
All rods in (ARI)	0.85362	0.96753	0.96919
ARI except D4	0.88363	0.99436	0.98980
ARI except D6	0.87723	0.98976	0.98732
ARI except D7	0.85657	0.97611	0.97845
ARI except E5	0.88150	0.99306	0.98875
ARI except E7	0.86366	0.97595	0.96963
ARI except F6	0.88026	0.99141	0.97795
ARI except MS	0.85627	0.96886	0.97063

uncertainties of the simulations are less than 4 pcm. It is clear that the core stays subcritical even during the worst possible stuck rod incident at the hot zero power condition (k_{eff} ~ 0.884 at "ARI except D4," where "D4" denotes the location of the assembly in the core; see Figure 2). As such, a hot shutdown operation can safely be assured with the proposed control rod pattern. The same is also true for the cold shutdown operation as the core stays subcritical even during the worst stuck rod condition at the cold zero power condition (k_{eff} ~ 0.994 at "ARI except D4"). The core nonetheless still depends on a secondary shutdown system (ie, emergency boron injection) to meet the mandatory PWR safety regulation. Table 4 also includes COREDAX-calculated k_{eff} at the cold zero power condition. Noticeable discrepancies are observed between the values calculated by Serpent and COREDAX, which are naturally expected due to the rather limited accuracy of the diffusion approximations in such a heavily rodded condition.

5 | CONCLUSIONS

This paper presents a preliminary investigation on the neutronic feasibility of a high-performance SBF SMR core by using the BigT BA. Three unique BigT designs are loaded region-wise in the SBF SMR design, resulting in a core BRS of only about 634 to 800 pcm, which is well within the desired SBF operational successful criteria. Furthermore, the cycle length of the BigT-loaded SBF SMR core can be long enough even with a single batch fuel management (~53 months) to achieve over 30 GWd/MTU burnup. The extremely small excess reactivity can be well and easily controlled by using gray MS rods. Safe cold shutdown operation can also be assured with a modified checker-board arrangement utilizing 95 w/o enriched B_4C absorbers. We can thus reasonably conclude that the SBF operation in the SMR core is potentially attainable with the strategic loading of the BigT absorber, MS, and shutdown bank rods. Demonstration of core arrangements capable of higher discharge burnups should be pursued in the follow-on optimization efforts.

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