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# A New Approach for a High-Performance Soluble-Boron-Free SMR Core

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## 1. Introduction

Removal of soluble-boron reactivity control from PWRs offers many significant improvements. Firstly, the risk of boric acid-induced corrosion in the primary system can effectively be eliminated. Secondly, an SBF core is possibly simpler in design, operation and maintenance than the conventional design. Thirdly, elimination of borated water from the primary loop greatly reduces radioactive waste volumes and water processing requirement associated with the deboration operation. Fourthly, an SBF core desirably maintains a large negative moderator temperature coefficient (MTC) at all times. Feasibility of an SBF PWR is generally accepted to be higher as the core power (hence core size) is reduced [1]. In addition, it is also known that cold shutdown is very challenging without the soluble-boron reactivity control, even for a small-sized core [2]. Nonetheless, a new approach for a high-performance SBF SMR core was recently proposed [3]. This paper aims to highlight results of the said investigation, which were completed using the Monte Carlo Serpent [4] and Coredax [5] diffusion codes with ENDF/B-7.1 nuclear data library.

## 2. SBF SMR Core Design

The SMR core modeled in this study is based on KEPCO E&C's small modular PWR design. Rated power of the reactor is 200 MWth while targeted cycle length for the single-batch fuel management operation is 48 months. Active core height is 2 m. The core is consisted of 37 fuel assemblies, each loaded with 4.9 w/o $UO_2$ fuel rods. Stainless steel reflector assemblies are used in place of the conventional baffle-reflector to reduce radial neutron leakage and, thus, enhance the core neutron economy. For a successful SBF operation, the burnup reactivity swing (BRS) throughout its operational cycle should be < 1,000 pcm [1].

### *2.1 BigT Absorber*

The main reactivity control system replacing soluble-boron in the SMR core is the "Burnable absorber-Integrated Guide Thimble" (BigT) absorber [6] as depicted in Figures 1 and 2. In this configuration, the BigT is simply a standard guide thimble but coated with azimuthally heterogeneous burnable absorber (BA) materials. Thickness and span of the BA can easily be adjusted per design requirement. In this study, the BA material of choice is 90 w/o $^{10}B$ boron carbide ($B_4C$).

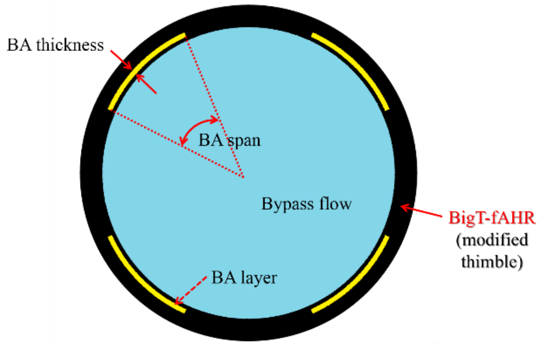


Fig. 1. Design concept of the BigT absorber.

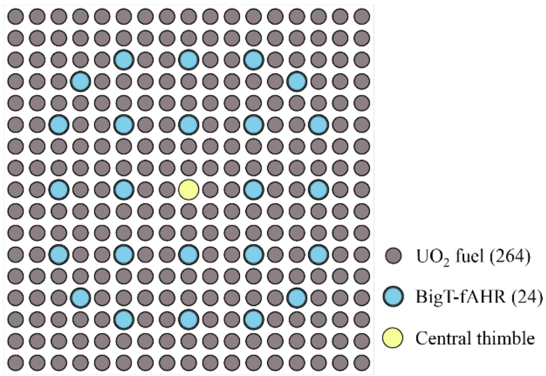


Fig. 2. A BigT-loaded fuel assembly.

### *2.2 BigT Loading Pattern*

This research took advantage of the neutronic flexibilities of the BigT design, in which thickness and span of its $B_4C$ were adjusted to attain the desired assembly reactivity suppression and depletion trend. Figure 3 clearly depicts this idea: three different BigT designs as tabulated in Table I with assembly depletion patterns shown in Figure 4 are loaded region-wise into the SMR core, whose effective combination enables the SBF operation of the core discussed subsequently.

Table I. Three BigT designs in the SMR core.

| FA (#) | $B_4C$ thick (mm) | $B_4C$ span (°) |
|---|---|---|
| FA-01 (9) | 0.090 | 70 |
| FA-02 (12) | 0.089 | 55 |
| FA-03 (16) | 0.019 | 60 |

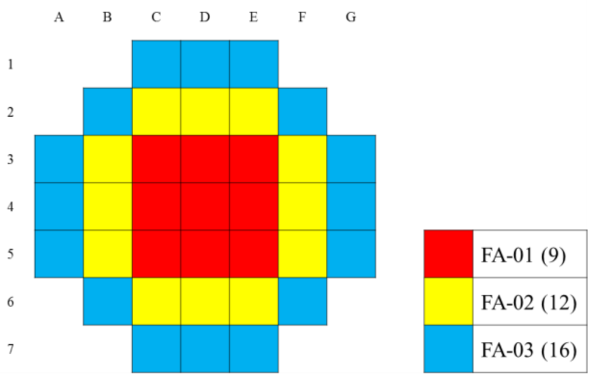


Fig. 3. BigT loading pattern.

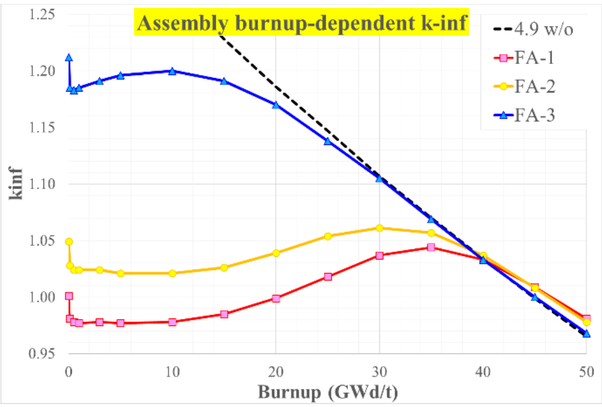


Fig. 4. Assembly neutronic characteristics.

### 3. Characteristics of the SBF SMR Core

Figure 5 depicts burnup-dependent k-eff trends of the BigT-loaded against the reference SMR core. The core BRS is clearly < 1,000 pcm as required. The BigT-loaded core also becomes subcritical earlier (30 GWd/t) than reference (31.5 GWd/t), indicating some $B_4C$ may have not been completely depleted at EOC. Nevertheless, the 54-month cycle actually exceeds the initial target of 48-month.

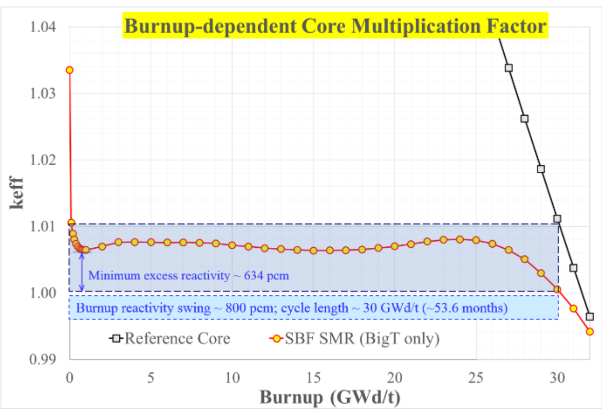


Fig. 5. Burnup-dependent k-eff trends of the reference non-poisonous and BigT-loaded SBF SMR cores.

A minimum of ~634 pcm excess reactivity is maintained almost throughout the operation so as to enable the SBF core to survive a possible sudden power drop in a big transient. This is because transient xenon worth in such a sudden power drop is rather limited. In addition, the transient xenon worth is actually substantially compensated by the power decrease itself; i.e., temperature feedbacks from both fuel and coolant provide some amount of positive reactivity since coolant temperature coefficient (CTC) is strongly negative (-50~-60 pcm/K) and fuel temperature coefficient (FTC) is also clearly negative (-2~-3 pcm/K). As such, temperature feedback itself can at least be several hundred pcm! This indicates that even smaller excess reactivity (e.g., 300~500 pcm) can also be acceptable in this SBF SMR operation.

Figure 6 depicts normalized radial power distributions in the BigT-loaded SMR core. Radial power distribution in the SBF core is clearly uniform (0.72~1.36) and, thus, quite practical.

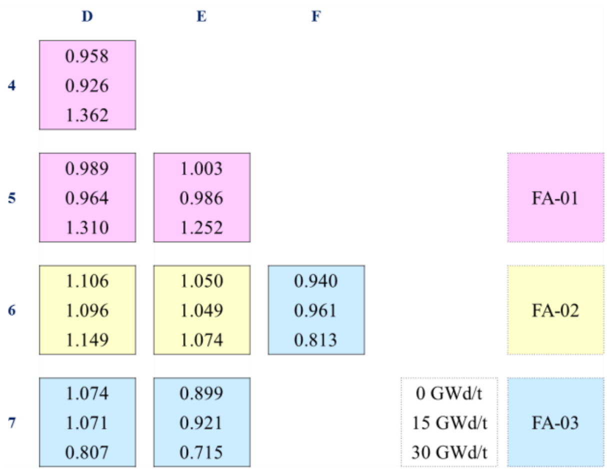


Fig. 6. Normalized radial power distribution.

Figure 7 shows evolution of the normalized axial power profiles of the BigT-loaded SMR core. As expected in a typical PWR design, the BigT-loaded core is bottom-skewed at BOC but gradually becomes slightly top-skewed at EOC.

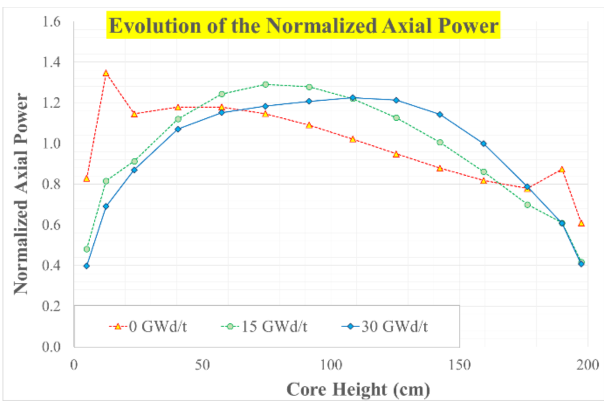


Fig. 7. Evolution of the normalized power.

## 4. Core Criticality Management

Since the BRS is kept relatively small < 1,000 pcm, the use of mechanical shim (MS) to attain the core criticality is also minimized, resulting in correspondingly small local power perturbations. Consequently, practically acceptable power distributions in the core can thus be attained. This is actually demonstrated in the following analyses.

It is assumed that all 37 assemblies in the BigT-loaded SMR core can be rodded according to the control rod pattern depicted in Figure 8. MS gray is 1.85 w/o hafnium-doped steel rod while shutdown and leading banks are 95 w/o $B_4C$ in inconel cladded rods.

Figure 9 depicts k-eff trend of the MS-rodded core. Small insertion of the leading banks is clearly necessary during the early burnup. Lifetime of the rodded SBF core is ~52.7 months. Figures 10 and 11 depict radial and axial power distribution in the rodded-SBF core. As expected, the MS gray rod operation only slightly perturbs the original profiles as its worth is relatively small (~600 pcm).

Table II tabulates k-eff values of the SMR core at clean BOC using the Monte Carlo Serpent code. Statistical uncertainties of the calculation are < 5 pcm. It is clear that the core stays subcritical even during the worst possible stuck rod incident at both HZP and CZP conditions (k-eff ~ 0.884 and 0.994, respectively, at 'ARI except D4'; refer Figure 8). As such, cold shutdown operation can safely be assured.

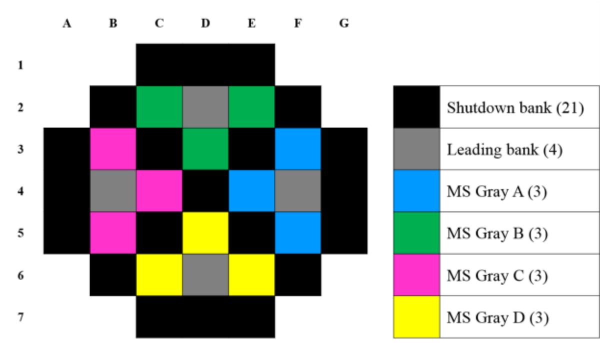


Fig. 8. Control rod pattern of the SMR core.

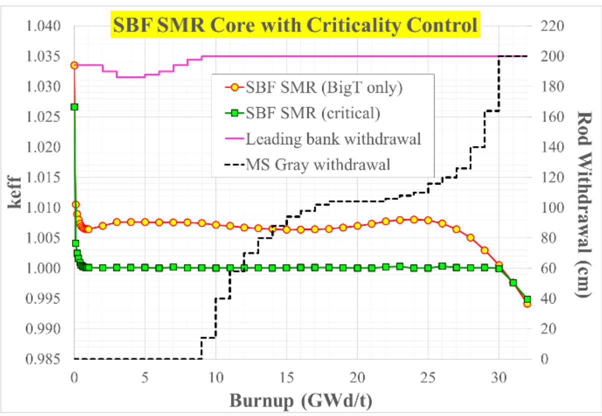


Fig. 9. Core criticality search with the rod withdrawal.

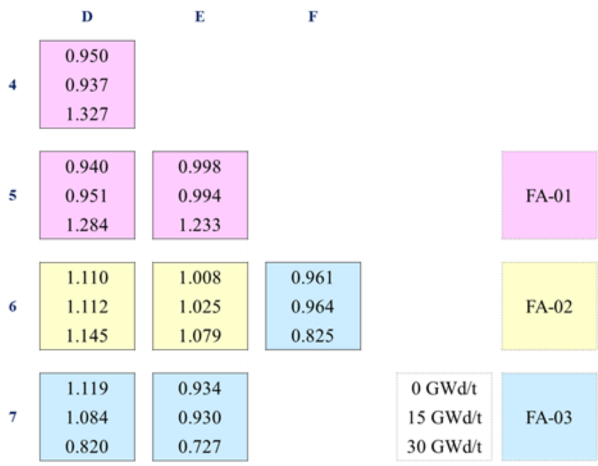


Fig. 10. Radial power profile of the SMR core.

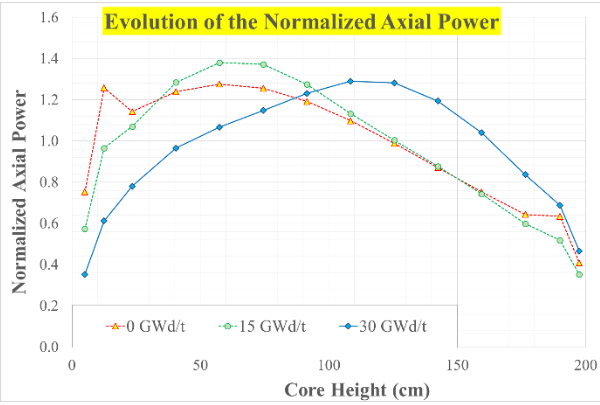


Fig. 11. Axial power distribution of the SMR core.

Table II. BOC clean k-eff at HZP and CZP conditions.

| BOC, no xenon | HZP (by Serpent) | CZP (by Serpent) | 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 |

## 4. Conclusions

Feasibility of a single-batch 200 MWth SBF SMR core is evaluated in this paper. Main reactivity control in the core is the newly-proposed BigT absorbers, which loads azimuthally heterogeneous 90 w/o $B_4C$ throughout all assemblies in the core. Spatial self-shielding of the BigT $B_4Cs$ are varied region-wise so as to attain the BRS < 1,000 pcm, which is a necessary requirement for a successful SBF PWR operation. Cycle length of the rodded-SMR core is ~52.7 months with very acceptable power distributions throughout the cycle. Core criticality and safe cold shutdown operations are also shown to be technically feasible with the proposed control rod patterns utilizing hafnium-doped stainless steels and highly-enriched $B_4C$ rods. Demonstration of core arrangements capable of higher discharge burnups should be pursued in the follow-on optimization efforts.

## ACKNOWLEDGMENT

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