# Neutronic Analysis of an Uprated Soluble-Boron-Free ATOM Core Design Based on the Centrally-Shielded Burnable Absorber

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## 1. Introduction

Recently, the PWR-type Small Modular Reactor (SMR) has become an attractive option for the energy mixes due to the integrated and simplified system, enhanced safety, flexibility features, and well-matured PWR technology [1]. In addition, the Soluble-Boron-Free (SBF) SMR core guarantees the inherent safety with a clearly negative Moderator Temperature Coefficient (MTC) [2]. However, the smaller core size results in the higher neutron leakage; therefore, the uranium utilization is lower than the typical PWR [3]. The elimination of the soluble-boron in the core means the MTC value is too much negative resulting in the challenges to meet the necessary criteria for the cold shutdown margin.

Recently, an enhanced-moderation Fuel Assembly (FA), so called Truly Optimized PWR (TOP) lattice, has been demonstrated to successfully increase the neutronic performance of a SBF SMR, named Autonomous Transportable On-demand reactor Module (ATOM) [4]. The enhanced moderation results in the less negative MTC; thus, the cold shutdown margin is reduced. The TOP lattice can be achieved by either changing the fuel pin pitch or reducing the fuel rod diameter.

In this study, the ATOM core power is uprated to 540 MWth while the active core height is increased to 240 cm. The TOP lattice is achieved by reducing the fuel pellet radius while preserving the FA size. An innovative cylindrical Centrally-Shielded Burnable Absorber (CSBA) is utilized to control the excess reactivity during the whole SBF SMR core operation. In addition, axial fuel enrichment zoning is applied to ensure a favorable and stable axial power profile. A checker-board Control Rod (CR) pattern with extended Control Element Assembly (CEA) is introduced to ensure the reactor cold shutdown condition. All calculations are performed by utilizing the continuous-energy Monte Carlo Serpent 2 code with ENDF/B-VII.1 nuclear library [5,6]

## 2. The ATOM Core Design

### *2.1 Truly Optimized PWR Lattice*

The standard 17x17 FA design for PWR is optimized under the soluble-boron condition to assure a negative MTC during the whole reactor operation. Thus, the FA is under-moderated. Therefore, by removing the soluble-boron, the Hydrogen to Uranium (HTU) ratio can be increased resulting in an enhanced moderation and higher reactivity. The softer neutron spectrum results in a sufficiently negative and similar MTC value throughout the reactor operation, which is favorable for a smaller temperature defect and larger cold shutdown margin, especially at the highly burned condition.

Based on the standard 17x17 FA, there are two ways to enhance the neutron moderation. First, by enlarging the pin pitch while fixing the fuel radius, and the second one is by reducing the fuel radius while preserving the FA size as illustrated in Figure 1.

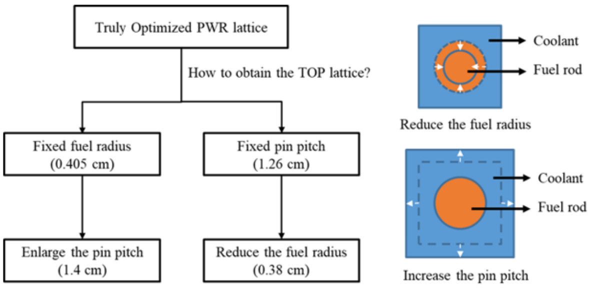
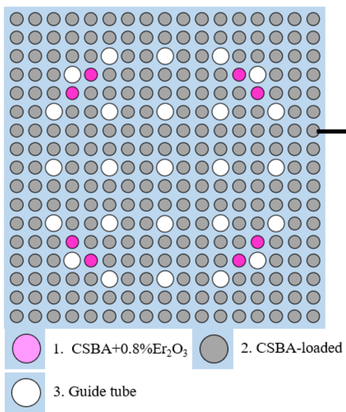
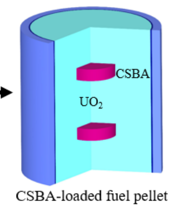



Fig. 1. TOP lattice designs.

In this study, the second approach where the fuel radius is reduced to 0.38 cm with the fixed 1.26 cm pin pitch is implemented. It should be noted that this approach results in the reduction of fuel inventory and increase in the specific power density increases proportionally. The detailed design of the TOP FA is depicted in Figure 2.




| TOP FA parameter | Value |
|---|---|
| Fuel pellet radius | 0.38 cm |
| Helium gap | 0.00915cm |
| Cladding thickness | 0.0573 cm |
| Pin pitch | 1.2623 cm |
| HTU ratio | 5.0 |
| FA pitch | 21.6038 cm |

Fig. 2. TOP CSBA-loaded FA design.

In this study, the TOP lattice with 5.0 HTU is utilized. Furthermore, the TOP lattice incorporates a small amount of Erbia ($Er_2O_3$) ~0.8% bearing fuel rods to reduce the early excess reactivity while minimizing the reactivity penalty at End of Cycle (EOC). These fuel rods are placed neighboring the guide tube to help reduce the local pin power peaking factors.

### *2.2 Cylindrical CSBA Design*

Gadolinia ($Gd_2O_3$) is a widely used BA material in LWRs due to its large neutron capture cross-section. However, the conventional 2-D BA design, such as gadolinia bearing fuel, depletes too quickly, making it difficult to manage the excess reactivity for whole reactor operation. To address this issue, a 3-D cylindrical CSBA is utilized to control the excess reactivity during the whole reactor operation. The cylindrical CSBA-loaded fuel pellet is depicted in Fig. 2.

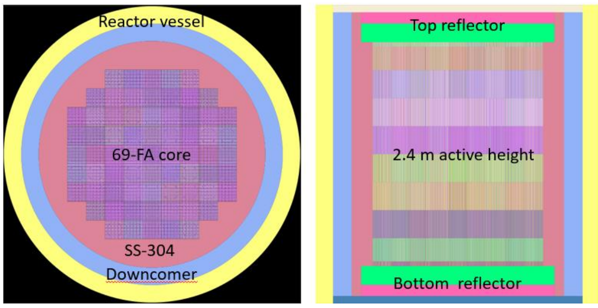
The self-shielding of the cylindrical CSBA can be customized by modifying the number of the CSBA cylinders per fuel pellet while keeping the BA volumes, and adjusting the height-to-diameter (HTD) ratio. In this study, the 2-cylindrical CSBA design with 89% Theoretical Density (TD) of Monoclinic $Gd_2O_3$ is used as the primary means of controlling reactivity in the core.

### *2.3 ATOM Core Design*

Table I: ATOM core design parameters

| Parameter | Value |
|---|---|
| Thermal power | 540 MWth |
| Fuel management | Two-batch |
| Active core height | 240 cm |
| Targeted cycle length | 2 years |
| FA type, number of FA | 17x17, 69 |
| Fuel density | 95.5% TD |
| Radial reflectors | SS-304 |
| BA design | Cylindrical CSBA |
| BA material | Monoclinic $Gd_2O_3$ |
| BA theoretical density | 8.33 g/cc |
| BA density | 7.40 g/cc (0.89% TD) |
| Targeted reactivity swing | 1,000 pcm |
| Inlet coolant temperature | 295.7 ℃ |
| Outlet coolant temperature | 323 ℃ |

The ATOM core design parameters and schematic layouts are presented in the Table I and Fig. 3, respectively. The core is designed to operate at 540 MWth power and loaded with 69 TOP-based 17x17 FAs with an active core height of 240 cm. The fuel management strategy adopts the two-batch scheme, with a targeted cycle length of two years. Each FA comprises of 264 fuel rods loaded with CSBA, 24 guide thimbles, and a central tube. Stainless-steel 304 (SS-304) is utilized as the radial reflector. The fuel enrichment is 4.95 w/o with 95.5% TD. A 5 cm blanket with 3.0 w/o enrichment is loaded at the top and bottom of the active core.




a. Radial view b. Axial view

Fig. 3. Schematic layout of the ATOM core (Serpent 2).

Figure 4 and Table II show the fuel loading pattern utilized in this study. An in-out fuel shuffling scheme is adopted to reduce the radial leakage and improve the neutron economy. Most of the feed FAs are loaded in the inner zone, while the once-burnt FAs are positioned in the peripheral zone. Several once-burnt FAs are loaded in the inner region to flatten the radial power distribution. The core has 34 standard feed FAs with 4.95 w/o $UO_2$, resulting in a rotationally symmetric core. Additionally, a special central with 3.0 w/o $UO_2$ is used to lower the central power peaking.

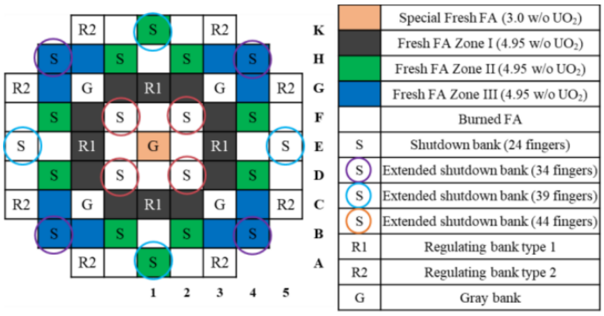



Fig. 4. Radial fuel-loading scheme and checker-board CR pattern.

Table II: The fuel shuffling scheme

| Zone I | | Zone II | | Zone III | |
|---|---|---|---|---|---|
| Fresh | Burned | Fresh | Burned | Fresh | Burned |
| 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 |

The CSBA is radially zoned to obtain a flat radial power distribution, as depicted in Figure 4. The largest cylindrical CSBA is loaded in the in the inner zone (Zone I) to lower the power peaking, while the smallest CSBA is loaded in the peripheral zone. Table III describes the CSBA parameters for each zone.

Table III: Radial zone-wise CSBA parameter

| Parameter | Zone | | | |
|---|---|---|---|---|
| | I | II | III | Center |
| Diameter (mm) | 3.30 | 2.66 | 2.42 | 2.66 |
| Height (mm) | 0.79 | 0.88 | 0.80 | 0.88 |
| H/D ratio | 0.28 | 0.33 | 0.33 | 0.33 |

The SBF operation has a clearly negative MTC since the Beginning of Cycle (BOC) resulting in a bottom-skewed power distribution due to higher coolant density at the core bottom. Therefore, the fuel enrichment is zoned axially to obtain a favorable and stable axial power distribution. The lower half of the core has a lower fuel enrichment compared to the upper-half. The axial fuel enrichment zoning is shown in Table IV.

Table IV: Axial fuel enrichment zoning

| Axial position (cm) | Zone | | | |
|---|---|---|---|---|
| | I | II | III | Center |
| 195-200 | 3 w/o | 3 w/o | 3 w/o | 3 w/o |
| 100-195 | 4.95 w/o | 4.95 w/o | 4.95 w/o | 3 w/o |
| 5-100 | 4.85 w/o | 4.85 w/o | 4.85 w/o | 3 w/o |
| 0-5 | 3 w/o | 3 w/o | 3 w/o | 3 w/o |

The ATOM core checker-board CR pattern is illustrated in Figure 4, comprising of 20 shutdown CEAs, 12 regulating CEAs, and 5 gray CEAs. The Shutdown Rod (SR) is loaded with 90 w/o B-10 $B_4C$, while 50 w/o B-10 $B_4C$ is adopted in the regulating rod. In this study, 12 SRs are extended by utilizing the empty fingers in the neighboring FAs (34, 39, or 44 fingers) to improve the cold shutdown margin. The Gray Rod (GR) is adopted to attain core criticality while minimizing the distortion of the axial and radial power distribution. Therefore, the GR worth should be similar to the burnup reactivity swing. In this study, Manganese is utilized as the GR material. Table V provides a summary of the CR materials.

Table V: The CR material for the ATOM core

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

## 3. Numerical Results and Discussion

The neutronic performance of the ATOM core is investigated using the continuous Monte Carlo Serpent 2 code with ENDF/B-VII.1 library. The calculation conditions are 200,00 histories per cycle with 300 active and 100 inactive cycles. The uncertainty of the effective multiplication factor ($k_{eff}$) is about 16 pcm. The effective fuel temperature is fixed at 900K, and a linearly-varying axial coolant temperature is considered with an inlet temperature 568.85K and an outlet temperature 596.15K. The corresponding temperatures for the Cold Zero Power (CZP) and Hot Zero Power (HZP) are 298K and 582.5K, respectively. The neutronic performances at the equilibrium cycle are presented in Figures 5 and 6.

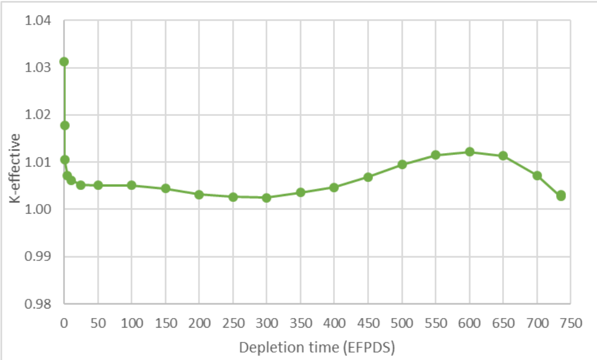



Fig. 5. The $k_{eff}$ evolution of equilibrium cycle.

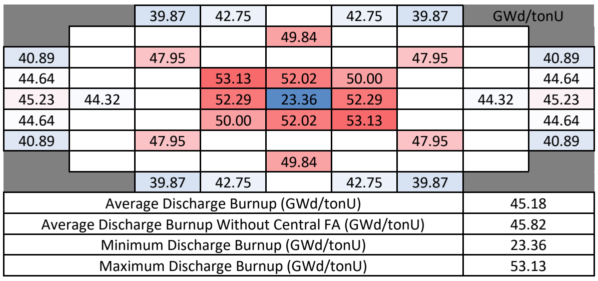
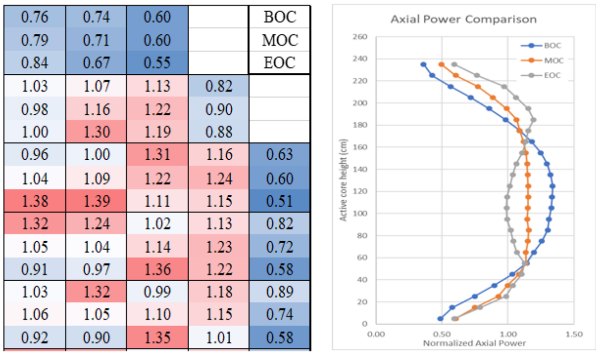



Fig. 6. Discharge burnup distribution.

It is clear that the CSBA successfully control the excess reactivity during the whole reactor operation. The reactivity swing is less than 1,2000 pcm while the targeted cycle length (2 years) is achieved. The reactivity swing is calculated as the maximum reactivity after the xenon equilibrium. The average discharge burnup is 45.82 GWd/tonU, which is quite comparable to the typical PWRs.

Figure 7 displays the radial and axial power distribution of the equilibrium cycle. The radial power peaking is relatively low, about 1.39 at the EOC condition, while the minimum radial power peaking is about 0.51 at EOC condition. The axial power peaking is only around 1.4 at the BOC condition. It is observed that the axial power distribution at BOC, Middle of Cycle (MOC), and EOC conditions are observed to be favorable and stable due to the utilized axial fuel enrichment zoning. The associated uncertainties for the axial and radial power are 0.14% and 0.22%, respectively.




a. Radial power b. Axial power

Fig. 7. Radial assembly-wise and axial core-average power distribution of the ATOM core.

Table VI tabulates the ATOM core temperature coefficients for various conditions. The MTC-BOC at Hot Full Power (HFP) is less than -53.2 pcm/K, which is sufficiently negative at any condition. Additionally, the MTC variation at HFP between BOC and EOC is minor, about -13 pcm/K. Therefore, the ATOM core is inherently stable throughout the reactor operation. The Fuel Temperature Coefficient (FTC) is about -2.66 pcm/K and -2.97 pcm/K at BOC and EOC conditions, respectively, which are typical values. The associated uncertainty of the MTC and FTC values are 0.42 pcm/K and 0.10 pcm/K, respectively.

Table VI: Temperature coefficients of the ATOM core

| Cases | BOC, no Xe | EOC*, no Xe |
|---|---|---|
| HFP-MTC (pcm/K) | -53.19 | -66.40 |
| HFP-FTC (pcm/K) | -2.66 | -2.97 |
| Temperature defect (pcm) | 6700 | 7701 |
| Power defect (pcm) | 909 | 985 |

*Evaluated at 600 Effective Full Power Days (EFPDs)

Table VII: Cold shutdown evaluation

| Case (@CZP) | BOC, no Xe | | EOC*, no Xe | |
|---|---|---|---|---|
| | $k_{eff}$ | Rod worth (pcm) | $k_{eff}$ | Rod worth (pcm) |
| ARO | 1.10023 | | 1.11538 | |
| ARI | 0.91057 | 18919 | 0.91500 | 19802 |
| N-1 (E1) | 0.91123 | 18847 | 0.91602 | 19691 |
| N-1 (E3) | 0.91522 | 18411 | 0.93902 | 17212 |
| N-1 (F2) | 0.97603 | 11978 | 0.96113 | 14884 |
| N-1 (F4) | 0.94957 | 14726 | 0.98256 | 12678 |
| N-1 (G3) | 0.95533 | 14121 | 0.94541 | 16534 |
| N-1 (H2) | 0.94937 | 14748 | 0.98053 | 12886 |

*Evaluated at 600 Effective Full Power Days (EFPDs)

Table VII presents the evaluation of cold shutdown margin for All Rods In (ARI) and N-1 conditions. The results show that the proposed CR pattern ensure the sub-criticality of the core. The ARI case has a margin less than 0.95, while all of the N-1 cases have a margin less than 0.99 for both BOC and EOC conditions.

## 4. Conclusions

In summary, the study successfully investigates the neutronic performance of the uprated two-batch ATROM core with reduced fuel pellet radius using the TOP-based lattice and two-cylindrical CSBA. The ATOM thermal power is uprated to 540 MWth and the active core height is increased to 240 cm. The results show that the proposed design achieves the targeted 2-year cycle length and the excess reactivity is successfully controlled by the cylindrical CSBA. The utilization of radially zoned CSBA results in a practical a radial power while the simple axial fuel enrichment zoning provides a stable and practical axial power distribution. The reactivity swing is small enough and sufficient to assure the SBF operation, while the discharge burnup is comparable to the typical PWRs. In addition. The utilization of TOP lattice results in a sufficiently and similar negative MTC throughout the reactor operation. Consequently, the reactor's inherent safety is guaranteed and the temperature defect is decreased. The proposed checker-board CR pattern also provides a sufficient and high cold shutdown margin. Overall, the study demonstrates the potential of the proposed design for practical and safe SBF operation.

As the power density is increased in the reduced fuel TOP, a comprehensive multi-physics analysis will be necessary and is planned for the future studies. Additionally, the rodded depletion analysis also will be conducted to ensure a more robust and practical application.

## Acknowledgement

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