# Boron-Free Small Modular Reactor Design by McCARD Burnup Calculation with T/H Feedback

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## 1. Introduction

There are many studies of small modular reactor (SMR) for several advantages of power supply to remote locations, seawater desalination, etc. [1]. Many of SMRs are designed for a soluble boron-free operation which can reduce the size of the nuclear power plant and the corrosion issues caused by boric acid. SMR needs a lot of burnable absorber (BA) and a reactivity control mechanism instead of soluble boron for reactivity control [2]. So, the arrangement of BA and the loading pattern of FA is important to make a stable reactivity [3].

In this paper, SMR is designed for 4 to 5 years of cycle length at 200MW thermal power considering design parameters. Monte Carlo (MC) burnup calculation with or without T/H feedback of SMR is performed by McCARD [4,5], and the results of the burnup calculation are compared. Based on the calculation result, analysis of the effective multiplication factor ($k_{eff.}$), radial and axial power distribution, and temperature distribution for the beginning of cycle (BOC), the middle of cycle (MOC), and the end of cycle (EOC) is conducted.

## 2. Core Design of Boron-free SMR

### *2.1 Core design parameters*

Table I shows the design parameters of boron-free SMR [3,6]. The thermal power of the core is 200 MW. The fuel assembly (FA) is based on the Westinghouse 17×17 FA. 52 FAs are loaded in the core. The fuel material is $UO_2$ with enrichment of 4.95 w/o. Solid Pyrex is used as BA. The active core height is 200 cm. There is no soluble boron in the moderator. The target cycle length and the maximum excess reactivity are selected to be 4 to 5 year, and within 5,000 pcm [6].

Table I: The design parameters of boron-free SMR

| Parameters | Value |
|---|---|
| Reactor type | PWR |
| Thermal power | 200 MW |
| System pressure | 15 MPa |
| Power density | 41.59 W/cc |
| Coolant & Moderator | Light water |
| Coolant Inlet Temp. | 563.15 K |
| Coolant Outlet Temp. | 598.15 K |
| Core Mass Flow | 997.5 kg/s |
| Boron concentration | 0 ppm |
| Number of FAs | 52 |
| Active core height | 200 cm |
| FA pitch | 21.50 cm |
| FA type | Westinghouse 17×17 |
| Fuel rod pitch | 1.26 cm |
| Fuel material | $UO_2$ |
| Fuel enrichment | 4.95 w/o |
| BA material | Solid Pyrex |
| Target cycle length | 4 ~ 5 year |
| Max. excess reactivity | < 5000 pcm |

### *2.2 Loading Pattern of SMR*

SMR is designed using FA loaded with Solid Pyrex. As shown in Figure 1, 24 BAs are loaded instead of fuel pins and their arrangement is decided according to the previous study [7]. The neutron absorption capacity of BA is proportional to the weight percent (w/o) of $B_2O_3$ contained in Pyrex. The core is composed of a combination of 5 types of FA with different concentrations of $B_2O_3$ in Pyrex. Table II shows the information of FA types by the concentration of BA. FAs using a high concentration of $B_2O_3$ are placed in the center of the core and FAs using a low concentration of $B_2O_3$ are placed in the periphery to make power distribution smooth in the radial direction. Figure 2 presents the loading pattern of SMR. In boron-free SMR, the reactivity change should be controlled by using the control rods. As shown in Figure 3, there are forty (40) Control Element Assemblies (CEAs) in the core for the reactivity control [8]. The location of CEAs is determined to control for normal operation and provide sufficient control rod worth to overcome the reactivity feedback caused by the core state change.

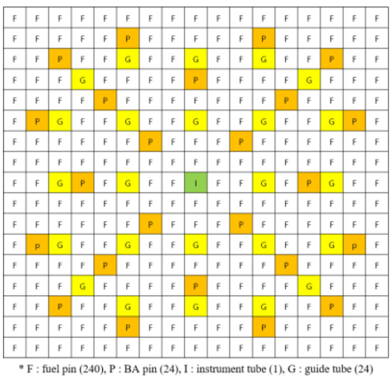



Fig. 1. Fuel assembly configuration

Table II: The information of FA types by the concentration of BA

| FA Type | $B_2O_3$ w/o in Pyrex | Number of fuel pins | Number of BA pins | Number of FA |
|---|---|---|---|---|
| 1 | 5 | 240 | 24 | 8 |
| 2 | 10 | 240 | 24 | 12 |
| 3 | 25 | 240 | 24 | 16 |
| 4 | 35 | 240 | 24 | 12 |
| 5 | 40 | 240 | 24 | 4 |
| Total | | 12480 | 1248 | 52 |

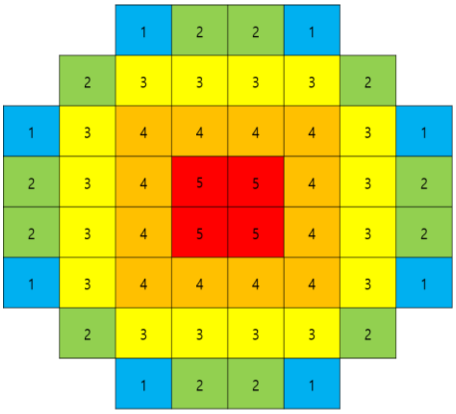
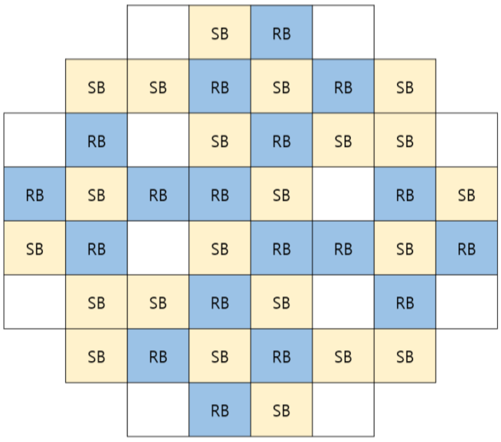



Fig. 2. Loading pattern of SMR




* RB: Regulating Bank (18), SB: Shutdown Bank (22)

Fig. 3. Location of the CEAs

## 3. McCARD Burnup Calculation with T/H feedback

The McCARD burnup calculation is performed with a built-in depletion equation solver based on the matrix exponential method [4]. McCARD has a pin-by-pin thermal-hydraulic feedback capability which considers only simple problems including coolant, gap, cladding, and fuel pellet [5, 9]. A radial temperature profile and an axial temperature profile in a fuel pin cell can be calculated by heat transfer equation and energy conservation equation for the 1-D T/H model. The T/H feedback calculation is conducted for a single pin cell using an assembly-wise averaged heat source and applies the same temperature for the pin cells in each assembly.

## 4. Numerical Results

The McCARD burnup calculation is conducted with 100,000 histories per cycle on 150 inactive and 300 active cycles using the continuous-energy cross section libraries produced from ENDF/B-VII.1. In the McCARD burnup calculation without T/H feedback, the average fuel temperature is 700K and the average coolant temperature is 580.65K. In the McCARD burnup calculation with T/H feedback, the inlet and outlet temperatures of the coolant are 563.15K and 598.15K, respectively. Under this condition, the temperature profile is determined by T/H feedback calculation.

### *4.1 The effective multiplication factor*

Figure 4 shows $k_{eff.}$ vs. burnup behavior with or without T/H feedback. The results present a similar tendency. The maximum cycle lengths calculated by result with and without T/H feedback are 4.9177 ± 0.0006 and 4.8864 ± 0.0009 years, respectively. The maximum excess reactivity is calculated as about 3800 pcm in both cases, which is less than 1200 pcm of the target value. Table III shows the difference of $k_{eff.}$ at BOC, MOC, and EOC. Overall, there are no significant differences between two graphs, and the maximum difference of $k_{eff.}$ is 175 pcm at 23.12 MWD/kgU.

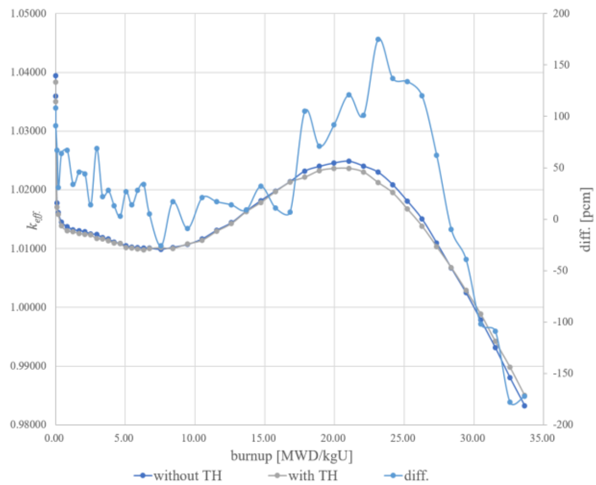



Fig. 4. $k_{eff.}$ vs. burnup behavior with or without T/H feedback

Table III: The difference of $k_{eff.}$ at BOC, MOC, and EOC

| Division | | without T/H feedback | with T/H feedback | Diff. [pcm] |
|---|---|---|---|---|
| Burnup [MWD /kgU] | EFPD [day] | $k_{eff.}$ (SD) | $k_{eff.}$ (SD) | |
| 0 | 0 | 1.03939 (0.00015) | 1.03831 (0.00013) | 108 |
| 16.82 | 1000 | 1.02140 (0.00013) | 1.02133 (0.00012) | 7 |
| 23.12 | 1375 | 1.02301 (0.00012) | 1.02126 (0.00012) | 175 |
| 29.43 | 1750 | 1.00248 (0.00012) | 1.00287 (0.00012) | -39 |

*4.2 Radial power distribution and temperature profile*

Figure 5 presents the comparison of radial power distribution with or without T/H feedback. In all cases, the maximum relative radial power is shown to be lower in the burnup calculation with T/H feedback. The maximum assembly power peaking factor is 1.334 ± 0.001 of the result without T/H feedback at EOC. The maximum difference and the root mean squared (RMS) difference are 3.35% and 2.84% at 23.12 MWD/kgU, respectively.

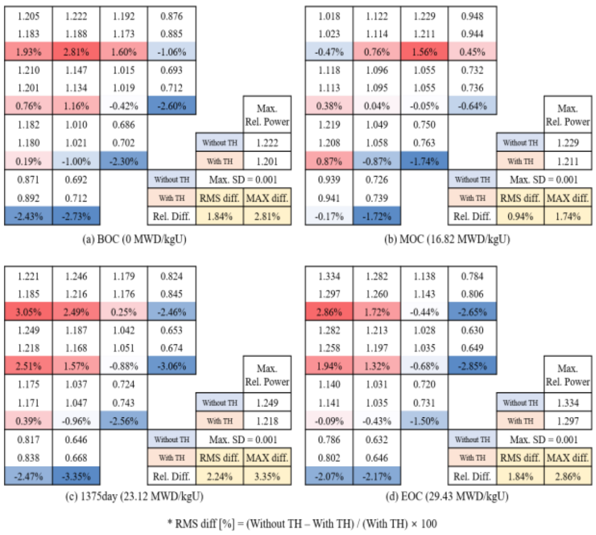



Fig. 5. The comparison results of the radial power distribution

Figure 6 shows the radial power distribution and the radial temperature profile calculated with T/H feedback. There is a power peak shift from the inner core region to the outer core region from BOC to MOC, and after MOC, a power peak moves vice versa. The maximum assembly power peaking factor is 1.297 ± 0.001 at EOC, where the average fuel temperature is 662.8 ± 0.964 K. The maximum radial pin power peaking factor is 1.4392 ± 0.0177 at EOC. The average fuel temperature of SMR is about 200 K lower than that of conventional PWR.

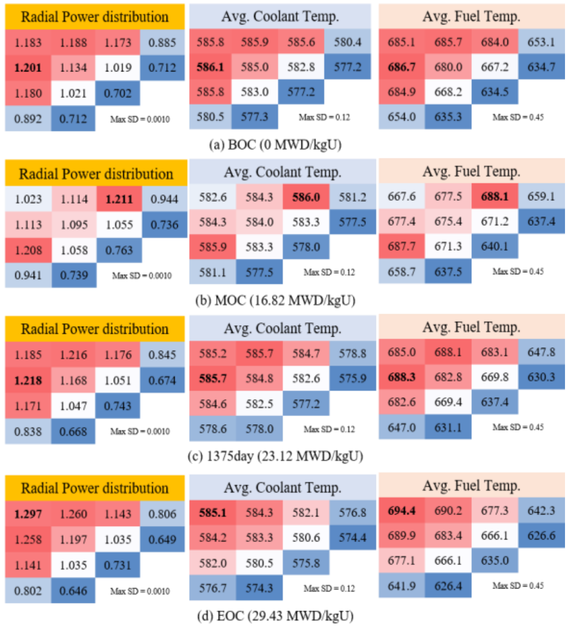



Fig. 6. The radial power distribution and temperature profile calculated with T/H feedback

*4.4 Axial power distribution and temperature profile*

Figure 7 shows the comparison results of the axial power distribution. The blue and orange line indicate the results with or without T/H feedback, respectively. The graphs of SMR maintains its cosine shape of axial power distribution longer than that of the conventional PWR until MOC. At 23.12 MWD/kgU, the axial power distribution in the center of the core are flattened in both graphs. Table IV shows the axial offset is within ± 0.40 in all cases [2].

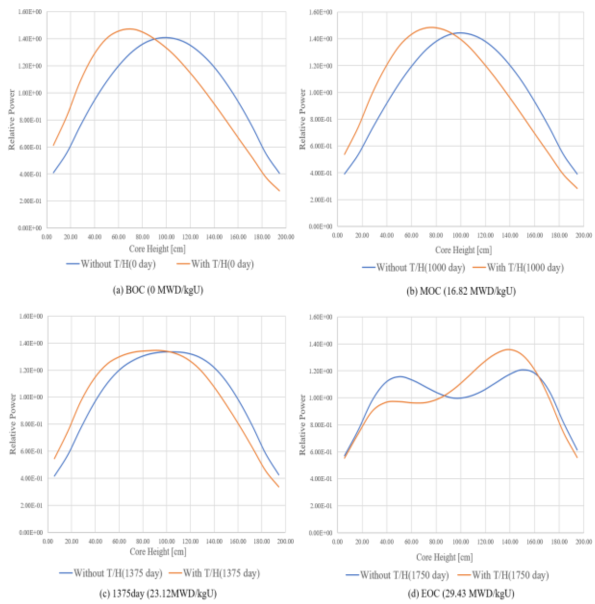



Fig. 7. The comparison results of the axial power distribution

Table IV: The axial offset

| Division | | without T/H feedback | with T/H feedback |
|---|---|---|---|
| Burnup [MWD/kgU] | EFPD [day] | Axial offset | Axial offset |
| 0 | 0 | 0.0044 | 0.2149 |
| 16.82 | 1000 | - 0.0013 | 0.1806 |
| 23.12 | 1375 | - 0.0071 | 0.1052 |
| 29.43 | 1750 | - 0.0210 | - 0.0979 |

Figure 8 shows the axial coolant and fuel temperature profile of the result with T/H feedback. In the axial direction, the maximum fuel temperature is 702.42 ± 0.96 K at EOC.

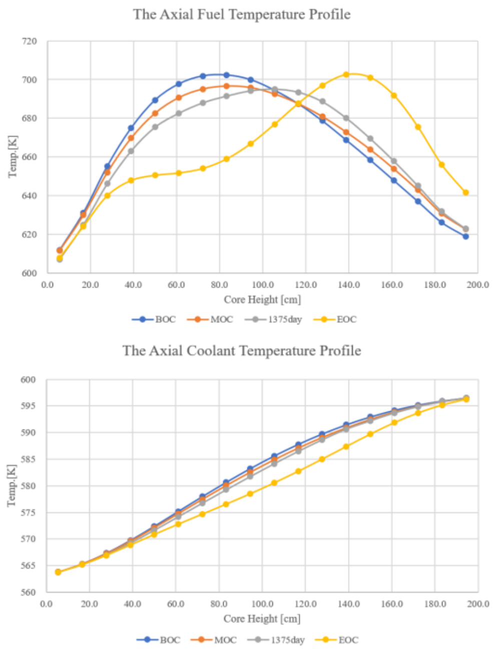



Fig. 8. The axial temperature profile of coolant and fuel

## 5. Conclusions

This paper presents the design of boron-free SMR by McCARD burnup calculation with T/H feedback. The core is designed using 5 types of assemblies with different concentrations of Pyrex burnable absorber satisfying the design parameters such as cycle length and the maximum excess reactivity with 200MW thermal power. The estimated cycle length is about 4.9 years and the maximum excess reactivity is around 3800 pcm. The result with T/H feedback shows that the maximum assembly power peaking factor is 1.297 ± 0.001 at EOC, and the maximum radial pin power peaking factor is 1.4392 ± 0.0177 at EOC. The average fuel temperature is 662.8 ± 0.964 K which is about 200 K lower than that of conventional PWR. For the axial power distribution, the cosine shape is maintained longer than that of PWR until MOC.

As for future work, it is necessary to calculate control rod worth, kinetics parameters, moderator temperature coefficient (MTC), and fuel temperature coefficient (FTC) with the control rod drive mechanism (CRDM).

## ACKNOWLEGMENTS

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