# A Small Modular Reactor Core Design using FCM Fuel and BISO BP particles

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## 1. Introduction

The effective long-term operation of current PWR nuclear power plants has significantly contributed on the effective generation of electrical energy, which led to the low price of electricity for our country. However, after the accident at Fukushima Dai-ichi, the public opinion slightly changed into the negative side on the nuclear energy because they have worries and doubts on the safety of nuclear power plant. Recently, many countries including USA have launched projects [1,2] to develop the accident tolerant fuels (ATF) which can cope with the accidents such as LOCA (Loss of Coolant Accident). In general, the ATF fuels are required to meet the PWR operational, safety, and fuel cycle constraints which include enhanced burnup, lower or no generation of hydrogen, lower operating temperatures, and enhanced retention of fission products. Another stream of research and development in nuclear society is to develop advanced small modular reactors in order to improve inherent passive safety and to reduce the risk of large capital investment.

The objective of this work is to design a PWR small modular reactor which employs the advanced fuel technology of FCM particle fuels [3-5] including BISO burnable poisons and advanced cladding of SiC in order to improve the fuel economy and safety by increasing fuel burnup and temperature, and by reducing hydrogen generation under accidents.

## 2. Methods and Results

### *2.1 Fuel Assembly Designs*

We considered the same power level of the SMART core (i.e., 330MWt) but 13x13 fuel assemblies having FCM TRIO particles whose UN kernel of 800μm diameter is surrounded by the four buffer layers. The thicknesses of the buffer layers and density of the UN kernel are determined through the discussion on the fabrication aspects with ORNL. These selections of the fuel and fuel assembly were from our previous work [6] on the fuel assembly-level neutronics and thermal hydraulics study. Table I summaries the main parameters of the fuel and fuel assembly. The fuel assembly was selected to be the same as that of the 17x17 Westinghouse type fuel assembly. Fig.1 shows the configuration of the fuel assembly which consists of 9 guide tubes and 160 fuel rods. In particular, it is noted in Fig. 1 that the fuel assembly has two different types of fuel rods : 1) 32 FCM fuel rods having no BP BISO particles and 2) 128 FCM fuel rods having BP BISO particles. We used a single uranium enrichment of 17.5% and a single value of fuel particle packing fraction (PF) of 40% for all the fuel rods. The kernel material of BP BISO particles is $Er_2O_3$ and its diameter is 250μm. To control power peaking, we considered five different fuel assemblies which has the same configuration as that given in Fig. 1 but they have different PFs of BP BISO particles. These fuel assemblies are designated as A1, B1, C1, D1, and E1 that have 2%, 3%, 4%, 5%, and 6% PFs of BP BISO particles, respectively. The active fuel height is 200cm and a 10 cm thick cutback region where BISO BP particles are removed is considered in the top region for axial power flattening. The fuel rod outer diameter and the lattice P/D (Pitch-to-Diameter) ratio are 1.3922cm and 1.1859, respectively. Table II summarizes the design parameters of the five different fuel assemblies described above.

Table I : Fuel and Assembly Design Parameters

| Parameters | Value |
|---|---|
| Fuel assembly pitch (cm) | 21.50 |
| Fuel pin pitch (cm) | 1.651 |
| Number of guide tubes | 9 |
| Guide tube inner radius (cm) | 0.72235 |
| Guide tube outer radius (cm) | 0.76835 |
| Fuel type | UN |
| Fuel density ($g/cm^3$) | 12.5125 |
| Fuel rod outer diameter (cm) | 1.3922 |
| P/D ratio | 1.1859 |
| Uranium enrichment (wt%) | 17.5 |
| Reference TRISO kernel diameter (μm) | 800 |
| TRISO buffer layer thickness (μm) | 80 |
| TRISO IPyC layer thickness (μm) | 20 |
| TRISO SiC layer thickness (μm) | 35 |
| TRISO OPyC layer thickness (μm) | 20 |
| BISO kernel diameter (μm) | 250 |
| BISO buffer layer thickness (μm) | 18 |
| BISO IPyC layer thickness (μm) | 23 |
| Cladding material | SiC |
| Cladding thickness (μm) | 400 |

Fig. 2 compares the evolutions of the infinite multiplication factors over depletion time. The depletion calculations for the fuel assemblies were performed using the DeCART2D code [7] and 47 group cross section library. As expected, the fuel assembly comprised of only cutback fuels has the longest cycle length but the largest excess reactivity. The other fuel assemblies effectively reduce the excess reactivity but have significantly reduced cycle lengths due to large reactivity penalties from the $Er_2O_3$ burnable poison.

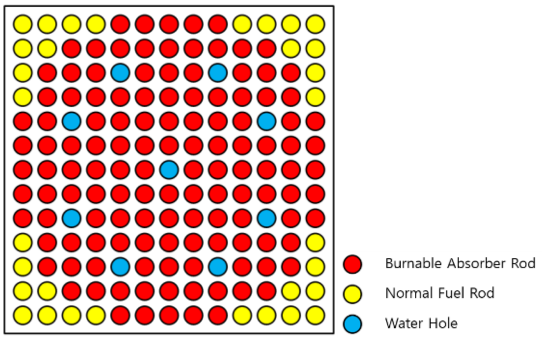


Fig. 1. Configuration of fuel assembly (FA)

Table II : Design Parameters of Different FAs

| FA Type | U Enrichment (wt%) | Number of BA rod | Packing Fraction | |
|---|---|---|---|---|
| | | | TRISO | BISO |
| A1 | 17.5 | 128 | 40 | 2 |
| B1 | 17.5 | 128 | 40 | 3 |
| C1 | 17.5 | 128 | 40 | 4 |
| D1 | 17.5 | 128 | 40 | 5 |
| E1 | 17.5 | 128 | 40 | 6 |

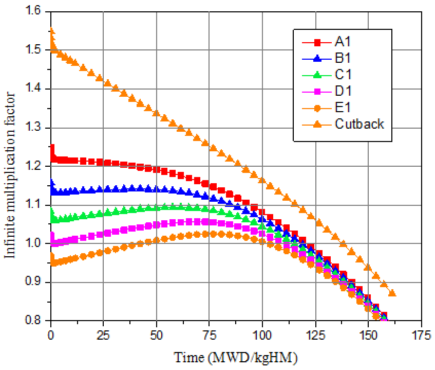
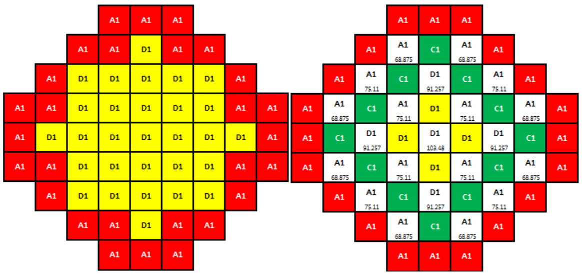


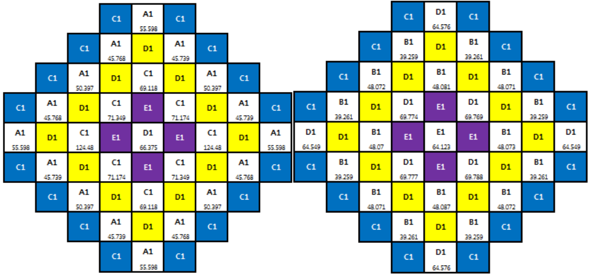
Fig. 2. Evolutions of $k_{inf}$ for the different FAs

*2.2 SMR Core Design*

The core rates 330MWt and it is comprised of 57 fuel assemblies described in Sec. 2.1. We performed the cycle-by-cycle reload core analysis using the MASTER code [8]. The core loading patterns for the cycles 1, 2, 3, and 4 are shown in Fig. 3. We adopted a two-batch refueling scheme which discharges 36 fuel assemblies having high burnup at the end of cycle (EOC) for all the cycles except for the first cycle at which 32 fuel assemblies are discharged. The fuel assemblies having white color represent the ones that are recycled from the previous cycle and the numbers given in these fuel assemblies means the accumulated burnup at the beginning of cycle (BOC). Fig. 5 shows the loading pattern and the accumulated burnups of fuel assemblies at EOC of the cycle 5 from which the cycle length and CBC (Critical Boron Concentration) are almost converged. In Fig. 4, the map of the control rods is shown.

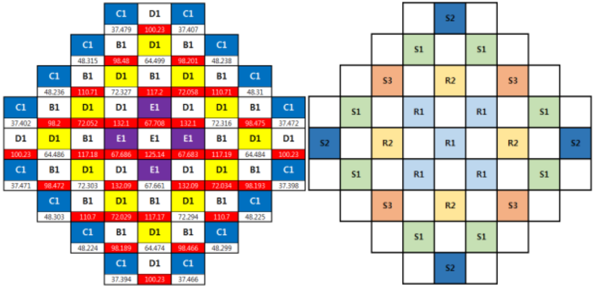


(a) Cycle 1 (b) Cycle 2



(c) Cycle 3 (d) Cycle 4

Fig. 3. Loading patterns of the cycles 1, 2, 3, and 4



(a) Loading pattern of cycle 5 (b) Control rod map

Fig. 4. Loading pattern of cycle 5 and control rod map

Table III summarizes the main performances of the reload cores from cycle 1 to cycle 7. As shown in Table III, the first cycle has the longest cycle length of 1192 EFPDs and the other cycle cores have similar cycle lengths of 732 ~ 744 EFPDs. The maximum CBCs of the first and the second cycles are 1066 ppm and 1193 ppm, respectively, while the other following cycles have much lower CBCs than these cycle cores. In particular, the seventh cycle core which can be considered as the equilibrium cycle core has the small CBC of 672 ppm. All the reload cores has maximum 3D power peaking factors ($F_q$) less than 2.2 and maximum radial power peaking factors less than 1.60 over the cycles. The reload cores have average discharge burnups 101~106 MWD/kg. Also, we analyzed the shutdown margins and the results show that all the reload cores have sufficiently large shutdown margins except for the fact that the first cycle core has relatively small shutdown margin of 3590 pcm at BOC. Fig. 5 compares the evolutions of CBCs over the cycles. Fig. 5 shows that the first cycle CBC slowly increases up to ~1000 ppm after a rapid drop and then it monotonically decreases while the CBCs of the cycles 2 and 3 monotonically decreases as time. For the other cycles, the evolutions of CBC are almost the same as each other. Fig. 6 compares the evolutions of the axial offset (AO) over the cycles. From this figure, it is shown that all the reload cores except for the first cycle one has very small ranges of AO and also the first cycle has the AOs which are within the typical design limit. Also, this figure shows that the evolutions of AO for the cycles 6 and 7 are nearly the same. Finally, the evolutions of MTC (Moderator Temperature Coefficient) both at HFP and HZP are compared in Fig. 7 which shows that all the cycle cores have negative MTCs over the cycles.

Table III : Comparison of the Performances of the Reload Cores

| Parameters | Cycles | | | | | | |
|---|---|---|---|---|---|---|---|
| | CY-01 | CY-02 | CY-03 | CY-04 | CY-05 | CY-06 | CY-07 |
| Cycle length (EFPDs) | 1191.9 | 743.9 | 732.0 | 744.0 | 740.9 | 741.7 | 741.4 |
| Maximum CBC | 1066 | 1193 | 898 | 677 | 672 | 672 | 672 |
| Maximum $F_q$ | 1.971 | 1.854 | 2.052 | 2.128 | 2.118 | 2.121 | 2.120 |
| Maximum $F_r$ | 1.451 | 1.526 | 1.549 | 1.595 | 1.594 | 1.594 | 1.594 |
| Average discharge burn up (MWD/kg) | 102.2 | 105.7 | 101.4 | 101.7 | 101.4 | 101.4 | 101.4 |
| Shutdown margin(%Δρ)<br>BOC / EOC | 3.590<br>/ 6.383 | 5.427<br>/ 5.891 | 5.554<br>/ 6.192 | 4.170<br>/ 6.474 | 4.174<br>/ 6.476 | 4.174<br>/ 6.476 | 4.174<br>/ 6.476 |

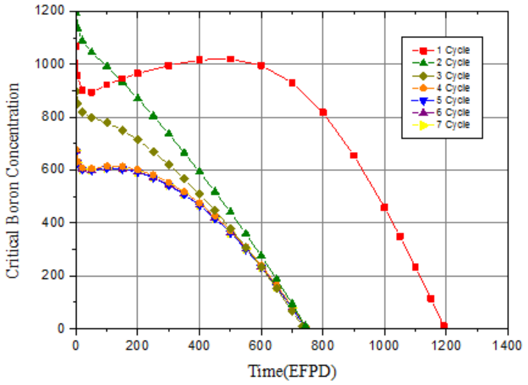


Fig. 5. Comparison of the CBC evolutions

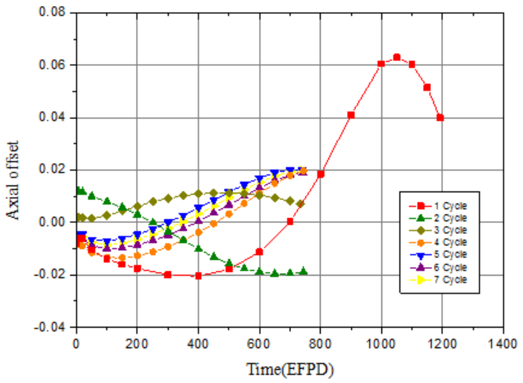


Fig. 6. Comparison of the AO evolutions

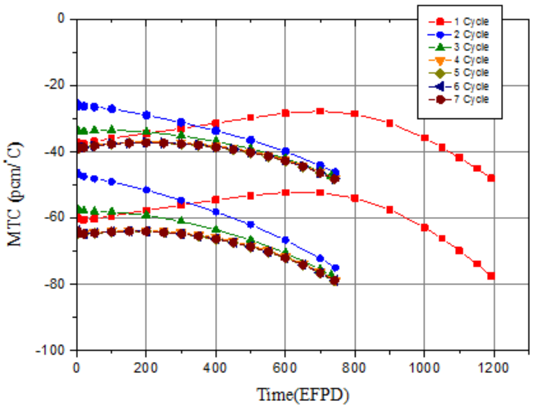


Fig. 7. Comparison of the MTC evolutions

## 3. Conclusions

In this work, a small PWR modular reactor core was neutronically designed and analyzed. The SMR core employs new 13x13 fuel assemblies which are loaded with thick FCM fuel rods in which TRISO fuel particles (UN kernel) and (or) BISO BP particles ($Er_2O_3$ kernel) are randomly distributed in SiC matrix. Also, we considered the SiC cladding for reduction of hydrogen generation under accidents. From the results of core design and analysis, it is shown that the core has long cycle length of 732 ~1191 EFPDs, high discharge burnup of 101~105 MWD/kg, low power peaking factors, low axial offsets, negative MTCs, and large shutdown margins except for BOC of the first cycle. So, it can be concluded that the new SMR core is neutronically feasible.

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