Design of Water-Cooled Small Modular Reactor Core with UO_2 Caramel Fuel

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1. Introduction

Recently, KEPCO Engineering & Construction company, Inc., and Seoul National University (SNU) are collaboratively developing an innovative small modular reactor (SMR) with fuel plates embedded with low enriched uranium oxide caramel fuel. Plate-type fuel has an advantage of large heat transfer area against pin-type fuel. The main purpose of this study is to design a plate-type water-cooled SMR core which satisfies design requirements of 180 MWth power and about four-year cycle length using 4.95 w/o enriched UO_2 fuel.

The SMR core design is performed in two levels by the SNU Monte Carlo code, McCARD [1]: fuel assembly (FA) design to make the longest cycle length in a predefined dimension and core design fulfilling its requirements with an optimization of the burnable absorber (BA) caramel loadings. A Monte Carlo (MC) neutron transport analysis code such as McCARD has an advantage to deal with complex geometry but takes too much time to optimize design parameters using MC calculations solely. To cope with this drawback, the linear multiplication factor model [2] is applied to efficiently search best design parameters in an FA design level. Then the core is designed by loading the fuel assemblies in a predefined core dimension and partly replacing UO_2 caramels by BA caramels to reduce the burnup reactivity swing. In this paper, two cores are presented according to the applied BA caramel types – B-SS used in a plate-type reactor of SHIPPINGPORT2 [3] and Gadolinia/Erbia.

2. Description of Plate-Type SMR

2.1. Design Requirement

Core height and radius of the plate-type SMR are 2.00m and 1.48m, respectively. Designed thermal power is 180MWth. The core cycle length should be over than four years. Maximum excess reactivity during burnup should be less than 3000pcm. The fuel enrichment is 4.95 w/o.

2.2. Core Configuration

The sectional views of plate-type FA and whole core are shown in Figure 1 and 2, respectively. Assembly pitch is the same as that of Westinghouse 17 × 17 FA, i.e., 21.522 cm. Height of the effective fuel assembly is 200 cm. The FA configuration is selected as the Seed 1 type FA of SHIPPINGPORT2 which has a cross shaped control blade sheath. A FA is composed of four sub-assemblies, each of which has 10 fuel plates. In a fuel plate, 13×76 caramels are embedded in Zircaloy-2 cladding. The width and height of a caramel are 7 mm and 25 mm, respectively. The thicknesses of a caramel, fuel plate and water channel determined from the FA optimization calculations are 4.30 mm, 5.30 mm and 4.78 mm, respectively. The whole core comprise 37 FAs and 8 sub-assemblies which are loaded in corner boundaries to increase the cycle length. Reflector is composed of steel.

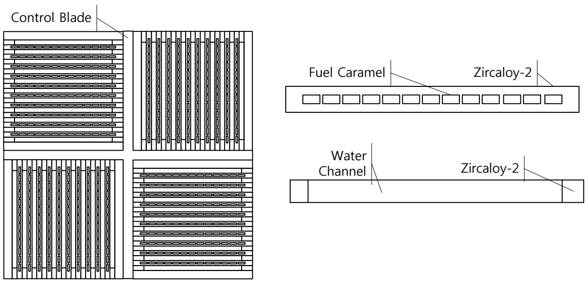


Fig 1. Sectional view of plate type SMR FA

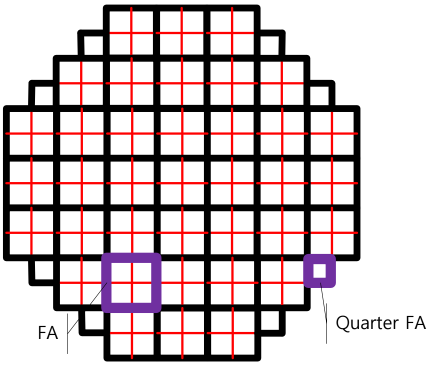


Fig 2. Sectional view of whole core

3. Assembly Optimization for Maximum Core Cycle

3.1. Linear Multiplication Factor Model

The linear multiplication factor model is based on the assumption that the multiplication factor of a nuclear system eventually decreases proportionally to burnup time as if there are no burnable absorbers. Therefore the multiplication factor k can be expressed as a function of burnup time:

$$k(t) = a \cdot t + k_0 , \tag{1}$$

where k_0 denotes the initial k value.

When the cycle length is defined by the time when the k value becomes 1, it can be calculated by

$$t = \frac{1 - k_0}{a} . \tag{2}$$

Assuming that a is determined solely by mass of initial fuel, one can predict the cycle length by Eq. (2) with pre-determined a value and k_0.

3.2. Optimization of FA Design Parameters

To design a FA which has the longest cycle length, 1,600 cases are considered with varying the fuel thickness, water channel thickness and number of plates per sub-assembly. Other dimensions such as clad thickness, blade thickness and number of caramels per plate are fixed. The design parameters that make the longest fuel cycle length are shown in Table 1. With the determined design parameters, the whole core MC burnup calculations are performed by McCARD with 200 inactive and 150 active cycles on 50,000 histories per cycle using ENDF/B.VII.0 data library. The core cycle length calculated by McCARD is 1,652 days.

Table 1. Optimized FA design parameters

Caramel thickness	Channel thickness	Number of plate per sub-assembly	Core cycle (McCARD)
4.30mm	4.78mm	10	1,652day

4. Core Design by Reducing Burnup Reactivity Swing

4.1. Outline

To control excess reactivity during core burnup, burnable poison needs to be loaded in FA. In order to decrease maximum excess reactivity during the core burnup, some fuel caramels can be replaced by BA caramels.

Three types of BA caramels—B-SS, Gd_2O_3-UO_2 and Er_2O_3-UO_2 are used. The concentration of BA caramel is determined by calculating residual poison reactivity penalty and those types are used to design the two types of cores. Throughout zoning BA caramels to high-power region, each core type is designed to lengthen core cycle and to decrease maximum excess reactivity.

4.2. Burnable Absorber Concentration

The concentration is determined with the case which residual poison reactivity penalty is less than 1000pcm at the end of the core cycle. 2D plate burnup calculations are performed to determine the concentrations. The sectional view is shown in Figure 3. A single BA caramel is loaded in the fuel plate with reflective boundary condition. The residual poison reactivity penalty is calculated by subtracting ρ with fuel-only plate problem ρ at the end of the core cycle.

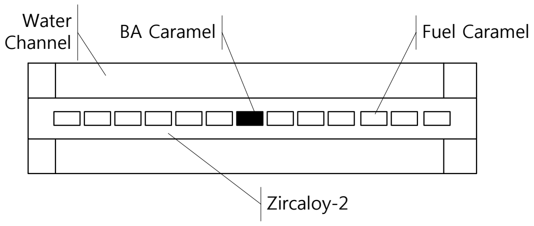


Fig 3. 2D plate modeling geometry

Determined concentrations of B-SS, Gd_2O_3-UO_2 and Er_2O_3-UO_2 are shown in Table 2. McCARD calculations are performed for 100 inactive and 50 active cycles on 10,000 histories per cycle with ENDF/B.VII.0 data library.

Table 2. Burnable absorber concentration

	B-SS	Gd_2O_3-UO_2	Er_2O_3-UO_2
concentration (w/o)	1.6	10	2.7

4.3. Burnup Calculation

In this section, two types of core are modeled by McCARD. In the first core, the excess reactivity is controlled by B-SS which is used in SHIPPINGPORT2 Seed1. In the second core, the excess reactivity is controlled by two types of uranium mixed fuels—Gd_2O_3-UO_2 and Er_2O_3-UO_2.

If initial k gets near the critical by inserting BA caramels, the shape of multiplication per time rate is expected to be flattened. Therefore, it is necessary to find the optimum number of BA caramel that makes initial k near critical. The calculation results about the core cycle and maximum excess reactivity are shown in Table 3. McCARD calculations are performed for 200 inactive and 150 active cycles on 50,000 histories per cycle with ENDF/B.VII.0 data library.

Table 3. Whole core depletion calculation by McCARD

First core		Second core	
Core cycle (day)	Maximum excess reactivity (pcm)	Core cycle (day)	Maximum excess reactivity (pcm)
1,128	3,759	1,258	3,841

The results show that second core has longer core cycle then the first core. But both cores do not satisfy the requirements of the core cycle and maximum excess reactivity.

4.4. Zoning BA to High-Power Region

Since a power distribution has cosine shape, burnable absorber caramels are relocated to the center axially and radially. Figure 4 shows the axial and radial zoning of poison caramel. In the first figure, caramels are relocated to the axial center. In the second figure, A, B, and C are assemblies that have different numbers of poison caramel. The total number of burnable absorbers is the same as the number before relocation.

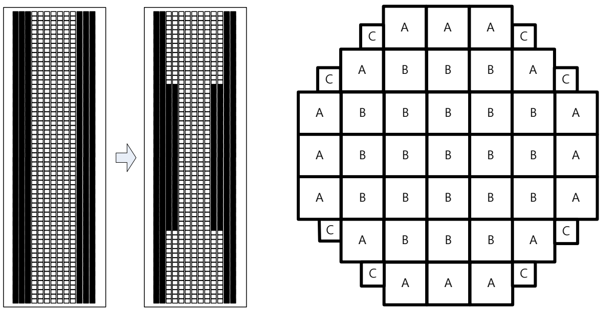


Fig 4. Axial and radial zoning of poison caramel

The MC depletion calculation results are following by Table 4. McCARD calaulations are performed for 200 inactive and 150 active cycles on 50,000 histories per cycle with ENDF/B.VII.0 data library.

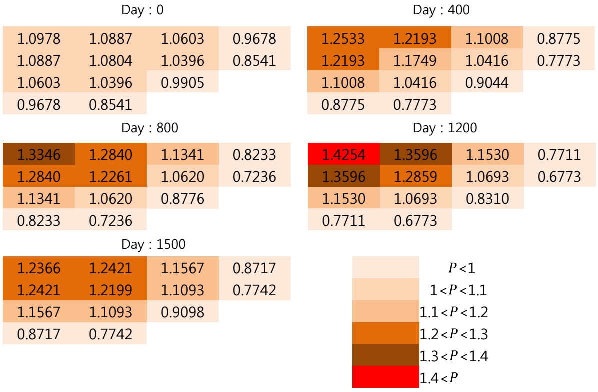
Table 4. Whole core depletion calculation by McCARD in the zoning case

First Core		Second Core	
Core cycle (day)	Maximum excess reactivity (pcm)	Core cycle (day)	Maximum excess reactivity (pcm)
1,321	2,236	1,509	2,746

The result shows that the zoning of burnable absorbers makes the core cycle longer and the maximum excess reactivity smaller compared to the results in section 4.3. The second core is satisfying the requirements and more improved against the first core by zoning.

4.5. Power Peaking Factor

The power distributions of each burnup step are shown in Figure 5. The core in this figure is the second type of core which used gadolinium and erbium mixed fuel caramel in section 4.4. During the burnup, maximum power peaking value is 1.4254 at 1,200 day.



Day : 0

1.0978	1.0887	1.0603	0.9678
1.0887	1.0804	1.0396	0.8541
1.0603	1.0396	0.9905	
0.9678	0.8541		

Day : 400

1.2533	1.2193	1.1008	0.8775
1.2193	1.1749	1.0416	0.7773
1.1008	1.0416	0.9044	
0.8775	0.7773		

Day : 800

1.3346	1.2840	1.1341	0.8233
1.2840	1.2261	1.0620	0.7236
1.1341	1.0620	0.8776	
0.8233	0.7236		

Day : 1200

1.4254	1.3596	1.1530	0.7711
1.3596	1.2859	1.0693	0.6773
1.1530	1.0693	0.8310	
0.7711	0.6773		

Day : 1500

1.2366	1.2421	1.1567	0.8717
1.2421	1.2199	1.1093	0.7742
1.1567	1.1093	0.9098	
0.8717	0.7742		

$P<1$
$1<P<1.1$
$1.1<P<1.2$
$1.2<P<1.3$
$1.3<P<1.4$
$1.4<P$

Fig 5. Whole core power distribution per time rate

5. Conclusion

The purpose of this study is to design a plate-type water-cooled SMR core which satisfies the design requirements. The maximum excess reactivity during burnup should be less than 3000pcm. To deal with the requirements, the FA design parameters are optimized by linear multiplication factor model. Moreover, in order to decrease maximum excess reactivity during the core burnup, some fuel caramels are replaced by BA caramels. Zoning of BA caramels to a high-power region decreases the residual poison reactivity penalty and maximum excess reactivity. BA mixed fuel caramels, i.e. Gd_2O_3-UO_2 and Er_2O_3-UO_2 have a good performance against B-SS which is used in a plate-type reactor of SHIPPINGPORT2. As a result, the second core design satisfied the design requirement. It is meaningful that plate-type core with complex geometry has been designed by McCARD solely.

ACKNOWLEDGMENTS

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