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Comparison of Predicted Breed-and-Burn Evaluation of a Small Modular Sodium-Cooled Fast Reactor with Several Code Systems

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1. Introduction

The Sodium-cooled Fast Reactor (SFR) is one of the Generation IV reactor concepts. Many SFR concepts have been proposed to take advantage of fast spectrum reactor. Authors proposed a 2600MW$_{th}$ Ultra-long Cycle Fast Reactor (UCFR-1000) for 60 year operation without refueling [1, 2]. A small size sodium-cooled fast reactor with a power level of 260MW$_{th}$ (UCFR-100) was also proposed based on the UCFR-1000 [3]. By making the core diameter smaller than 3m and the core barrel transportable from the pre-licensed factories to the remote plant site, the proposed reactor can be considered small modular reactor (SMR) [4].

The small modular sodium-cooled fast reactor (SM SFR) in this study adopts a breed-and-burn strategy. The core lifetime and breeding directions are investigated using a fast reactor analysis code system (MC^2-3/TWODANT/REBUS-3) and Monte-Carlo code (McCARD) as a reference solution [5-8]. For the SM SFR core design, this research can be a preliminary study by comparing the results of the fast reactor analysis code system with that of the Monte-Carlo code.

2. Core Designs

There are 5 types of core designs selected as SM SFR core models. In order to design SMRs, the core size is reduced from that of UCFR-1000. The 280cm diameter by 100cm height core contains 144 fuel assemblies, 102 reflector assemblies and 7 control assemblies. Each core has different fuel assemblies in terms of fuel composition and the position of the blanket region. The difference of fuel composition in each core leads to different breeding behaviors. The 5 types of core can be categorized according to their breeding behavior.

The fuel assembly contains 91 fuel pins enclosed by structure material. The fuel material is U-10Zr, and the cladding and structure materials are HT-9 [9]. Sodium is filled in the core as a coolant material. The uranium enrichment in the fuel pins varies depending on the core type. All the analyzed cores are SMRs with a power level of 260MWth. The target lifetime of the cores is 30 years for the ultra-long cycle concept. Figs. 1 and 2 show the core radial configuration and the axial fuel distribution of the 5 core types, respectively.

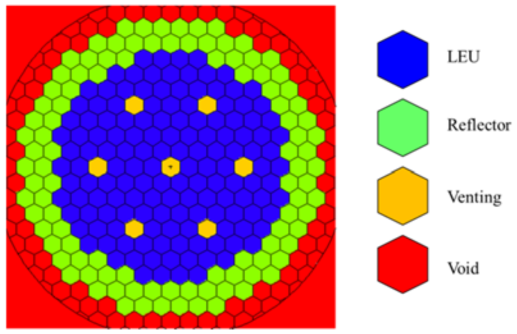

Fig.1. Radial core configuration of SM SFR.

2.1 Uniform enrichment

The first core type has a uniform enrichment core. Overall, fuel assemblies have the same compositions. Uranium with 11.3% enrichment is used in the fuel material of U-10Zr.

2.2 Onion zoning

The second core type is an onion zoning core. The fuel of the LEU region uses 12.6% enriched U-10Zr. The blanket region, which consists of natural uranium, is located at the center of the core. Through the depletion, the blanket region will turn into an active core.

2.3 Axial breeding

The third core type is an axial breeding core. The blanket region contains the same composition as the blanket region of the onion zoning core. The blanket region is located at the top of the core, so the active core can move to the upper zone of the core. The fuel of the LEU region uses 13.5% enriched U-10Zr.

2.4 Axial-dual breeding

The fourth core type is an axial dual breeding core. The blanket region is located at the center of the core, axially enclosed by the LEU region. The fuel of the LEU region is 19.5% enriched.

2.5 Radial breeding

The last core type is a radial breeding core. The fuel assemblies located at the second and third rings are the blanket region. The blanket region is enclosed by the 13.3% enriched LEU region.

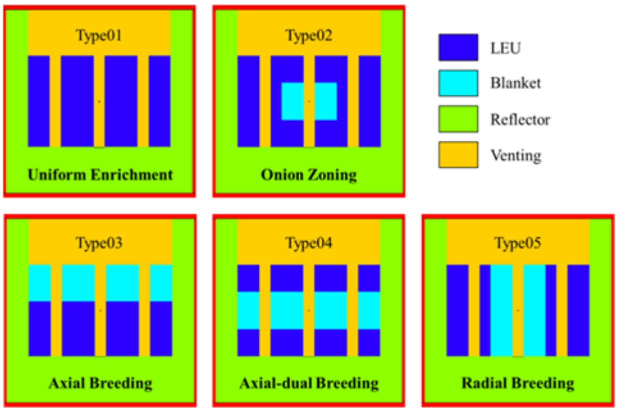

Fig.2. Axial fuel distribution of 5 types of core.

3. Computer Code Systems

In this paper, the ANL fast reactor analysis code suite was used for the simulation of the aforementioned five core types. In order to identify the core lifetime and core performance, depletion calculations were carried out. Thirty burnup steps are used for depletion with each step being 1 year. For comparison purpose, Monte-Carlo calculations were also performed.

3.1 Deterministic code system

For analyzing the fast spectrum reactor, a fast reactor analysis code system is used. Generating a multi-group cross-section for a fast reactor is conducted by MC^2-3. MC^2-3 solves the consistent P_1 ultra-fine-group neutron slowing down equation using ENDF/B-VII.0 to determine the fundamental mode neutron spectra for use in generating fine-group neutron cross-sections. TWODANT in the DANTSYS code package solves the time-independent, multi-group discrete ordinate form of the Boltzmann transport equation. REBUS-3 is a system of programs designed for the analysis of fast reactor fuel cycles. REBUS-3 has various neutronics solution algorithms such as finite difference, spatial flux synthesis, and nodal diffusion theory methods to provide the flux solution.

At the first step of fast reactor analysis, TWODANT with MC^2-3 generates the region-wise flux spectra. After generating fluxes, MC^2-3 condenses to broad-group cross-sections using flux spectra. Lastly, the nodal diffusion calculation is performed by using the 33-group cross-section in REBUS-3. Fig. 3 shows the fast reactor analysis flow.

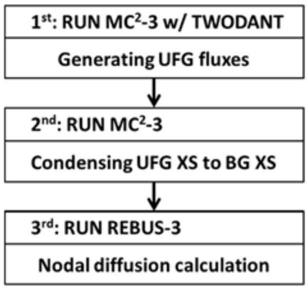

Fig.3. Fast reactor analysis flow.

3.2 Monte-Carlo code

For the comparative neutronic calculations, the Monte-Carlo code is used to provide the reference solutions. The McCARD code was used. The McCARD code is a Monte-Carlo code for analyzing and designing an advanced reactor.

The Monte-Carlo code uses the ENDF/B-VII.0 continuous energy cross-section. The Monte-Carlo simulation parameter is set to 100,000 histories per cycle with 200 active cycles and 50 inactive cycles. The simulation parameter was decided to make standard deviation as 10pcm for every depletion step.

4. Analysis Results

In this section, the calculation results such as effective multiplication factors, breeding ratios, and power distributions are presented. From the initial state calculation, the effective multiplication factor is calculated by TWODANT, REBUS-3, and Monte-Carlo code. Depletion calculations using REBUS-3 and McCARD for 30 years give effective multiplication factors at each burnup step. The breeding ratio is calculated at each depletion step. Also, the total amounts of major isotopes at every depletion step are calculated for comparison of the codes. Lastly, the power distribution is calculated in order to figure out whether the active core moves in the right direction and the breeding occurs as expected in the blanket region.

4.1 Effective multiplication factor

The depletion calculations for each core type are carried out for 30 years using REBUS-3 and McCARD. Fig. 4 shows the effective multiplication factors for the 30 year depletion calculation by REBUS-3 and McCARD. The trends of multiplication factors are similar between the results of each code. And the differences of effective multiplication factor are smaller than 200pcm for Type 01, 02, and 03 cores. Because the breeding behavior was applied differently in each codes and axial and axial-dual breeding core have larger breeding effect than other cores, the difference of multiplication factor of Type03 and 04 cores were larger than other types.

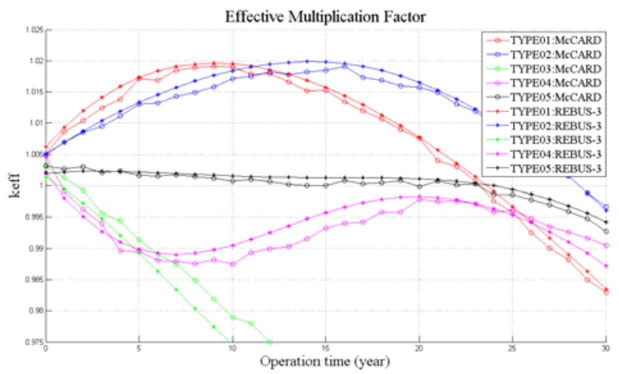

Fig.4. Multiplication factors by REBUS-3 and McCARD.

Table I shows the reactivity swing during the 30 years depletion calculation for each core type. The Type 05 core, i.e. the radial breeding core, shows the smallest reactivity swing. But, the difference of reactivity swing between REBUS-3 and McCARD for Type 03 core is largest. As aforementioned, if breeding effect is larger than other core type, the difference of reactivity swing between codes could be larger.

Table I. Reactivity Swing during 30 year Depletion

Core	$\rho_{max} - \rho_{min}$ (pcm)	
	REBUS-3	McCARD
Type 01	3603	3601
Type 02	2338	2200
Type 03	6401	5972
Type 04	1512	1748
Type 05	809	1050

4.2 Breeding ratio

Because the Type 05 core, the radial breeding core, has the largest blanket region, breeding ratios and the amount of isotopes could be emphasized to show the differences between codes. Table II represents the breeding ratio of the Type 05 core during the depletion calculation. In this study, the breeding ratio was defined by the ratio of the total fissile number densities of ^{235}U and ^{239}Pu at discharge and charge states. Both codes show similar breeding ratios.

Table II. Breeding Ratio of Radial Breeding Core

Code	Breeding ratio			
	0 years	10 years	20 years	30 years
REBUS-3	0.728	0.808	0.854	0.869
McCARD	0.729	0.806	0.854	0.871

4.3 Total amount of isotope

Fig. 5 shows the difference of total amounts of major isotopes in the reactor during the depletion calculation for the Type 05 core. The amounts of ^{235}U, ^{238}U, and ^{239}Pu match well between REBUS-3 and McCARD. The difference of ^{241}Pu is bigger than these of other isotopes, but amount of that isotope quite so small, therefore that can be negligible.

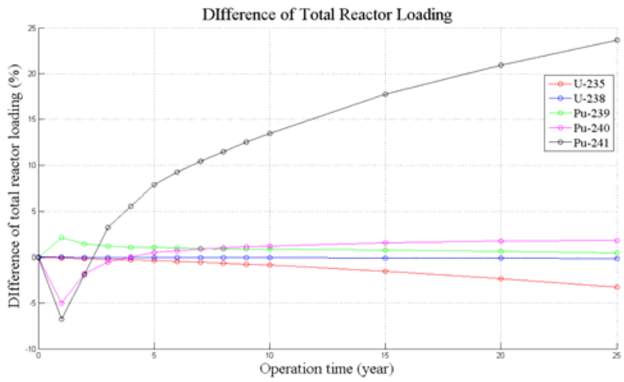

Fig.5. Difference of total reactor loading of major isotopes.

4.4 Power distribution

From the multiplication factors trends for 30 years, both Type 02 and Type 05 cores show a small reactivity swing and have lifetimes longer than 20 years. By analyzing the power distribution, it is easily noted that each core design performed well with the right breeding directions.

Fig. 6 shows the R-Z layout of normalized power distribution of the Type 02 core, i.e. the onion zoning core. The red color represents the high power region and the green color represents the low power region. Because the bottom of the core consists of a reflector assembly, the power at the bottom of the core is higher than that of the top of the core. The blanket region located at the center of the core has lower power at the initial state. By depletion, breeding occurs in the blanket region, and the active core moves to the center of the core. The power at the center of the core by REBUS-3 is smaller than that calculated by McCARD. This lower power means that the active core moves more slowly and a smaller amount of breeding occur.

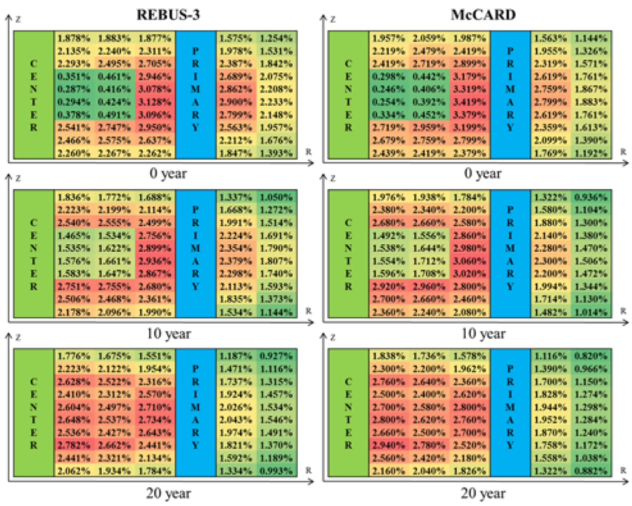

Fig.6. R-Z Layout of Power distribution of onion zoning core.

Fig. 7 represents the R-Z layout of normalized power distribution of the Type 05 core, i.e. the radial breeding core. The trend of axial power distribution is similar with the onion zoning core. Similarly with the onion zoning core, the power in the blanket region by REBUS-3 is smaller than that by McCARD.

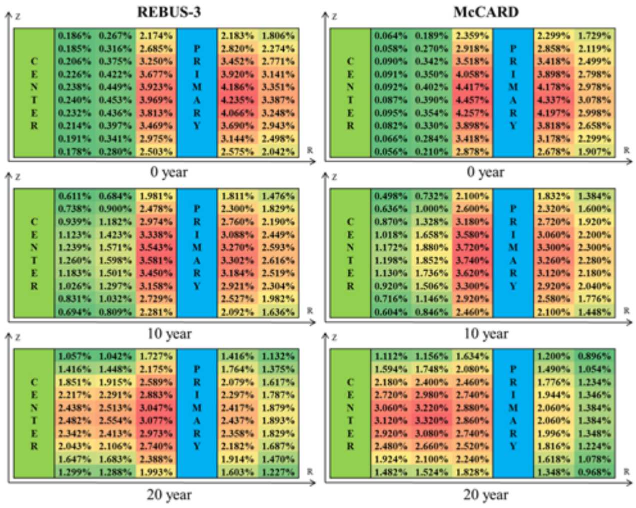

Fig.7. R-Z Layout of Power distribution of radial breeding core.

5. Conclusion

Five types of small size sodium-cooled fast reactor core design are analyzed by both fast reactor analysis code system and Monte-Carlo code. Each core has different enrichments and breeding directions. The breeding direction is determined by the location of the blanket region. The multiplication factor during the depletion shows similar trends between REBUS-3 and McCARD. Also, the differences of multiplication factor are quite small between both codes. However, if the core has big blanket region, in other words, the breeding effect is dominant, the difference of multiplication factor during depletion calculation could be larger. It can be noted that the onion zoning core shows the longest lifetime among the core types. At the same time, the radial breeding core shows the smallest reactivity swing. From the breeding ratio and total amount of major isotopes, it can be noted that both codes are similar in terms of breeding. The normalized power distribution shows whether breeding occurs reasonably or not and how the active core moves. From the analysis results, it can be noted that the active core calculated by REBUS-3 moves slower than that of McCARD.

Acknowledgements

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