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Evaluation of the Flexible Operation Capability of an i-SMR Core Using RCS Outlet Temperature-Based Control Rod Operation Method

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1. Introduction

Innovative-Small Modular Reactor (i-SMR) is based on the soluble boron-free core design as one of its key requirements, which is characterized by the continuous insertion of control rods to make the core be critical state and an extremely large negative moderator temperature coefficient (MTC). [1]

In the i-SMR, a reactivity control concept utilizing a very large moderator feedback effect is being considered as a secondary reactivity control system with an independently different operating principle, as required by General Design Criterion 26 of Appendix A to Part 50 of 10 CFR, and studies are being conducted to assess its feasibility. [2][3][4]

Adopting an RCS temperature program designed to decrease the core average temperature as the core power increases enables efficient derivation of the reactivity required for core power change. This is achieved in conjunction with the powerful reactivity feedback effect resulting from the strongly negative MTC characteristic of a soluble boron-free core.

Based on this fact, it may be possible to minimize changes in the core power distribution and ensure the mechanical integrity of the control rod drive mechanism by reducing the burden on control rods, which are used to compensate for the reactivity changes inevitably induced during power variations in soluble boron-free core.

This paper aims to quantitatively simulate the behavior of control rods in the i-SMR core, which employs a combination of a strongly negative MTC and an appropriate RCS temperature program to regulate reactivity changes. This assessment is conducted through reactivity control simulations for a specific example of flexible operation.

2. Methods and Procedures

2.1 Computational Methods

Assembly burnup calculations for two group cross section generation were calculated by KARMA (Kernel Analyzer by Ray-tracing Method for fuel Assembly) which is a two-dimensional multi-group lattice transport code using 190 group and 47 group cross section library based on ENDF/B-VI.8. This code uses the subgroup method for resonance self-shielding effect and MOC (Method of Characteristics) as the transport solution method. [5][6]

For 3D core modeling and simulation with various core conditions, ASTRA code was used. [7] ASTRA code is a 3D core depletion code and developed by KEPCO NF (KEPCO Nuclear Fuel) as a nuclear design code for the core design of pressurized water reactors (PWRs) based on the reactor physics technologies. ASTRA has the neutronics solver based on the Semi Analytic Nodal Method (SANM) formulated with the Coarse-Mesh Finite Difference method (CMFD). [8][9]

2.2 Overview of i-SMR Core Design

The i-SMR, designed for a thermal power of 520 MW, consists of 69 fuel assemblies with a 17 × 17 lattice structure and an active core length of 240 cm. The U-235 enrichment used is up to 4.95 w/o. The assembly configuration for i-SMR incorporates an arrangement of fuel rods with low-enriched uranium and burnable absorbers of Gd_2O_3-UO_2 with enriched gadolinium to effectively prevent excessive peak power and evenly suppress excess reactivity over time during. The control rods for regulation, which consist of 28 Ag-In-Cd pins, are classified into four groups—R4, R3, R2, and R1—positioned as shown in Fig. 1, based on their insertion order. During power operation, the three groups—R4, R3, and R2—are typically inserted and withdrawn while maintaining a 120 cm spacing between each group.

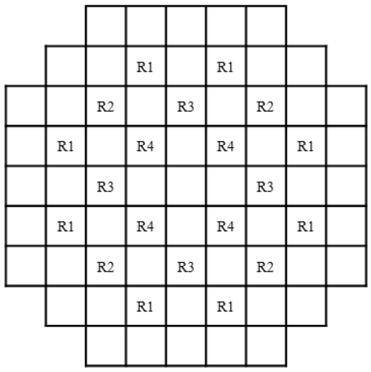

Fig. 1 Regulation Bank Pattern of i-SMR

2.3 Calculation Procedures for Daily Load-follow Operation

The control rod operation method to regulate reactivity assumed in this study is based on detecting a fluctuation of the RCS outlet temperature. In this method, the control rods move only when the outlet temperature exceeds the allowable range established for each power level, ensuring that the outlet temperature returns to the desired value. The available deviation of the RCS outlet temperature is assumed to be ±2°C, considering the variation range from HFP to HZP. The outline of control rod operation is briefly illustrated in Fig. 2.

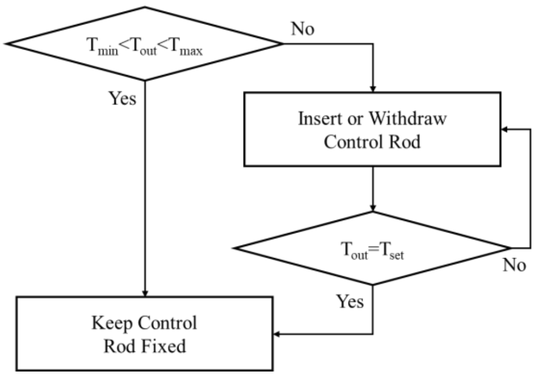

Fig. 2 Outline of Control Rod Operation

Fig. 3 shows the RCS temperature program of i-SMR including the allowable outlet temperature deviation of ±2°C (dotted line).

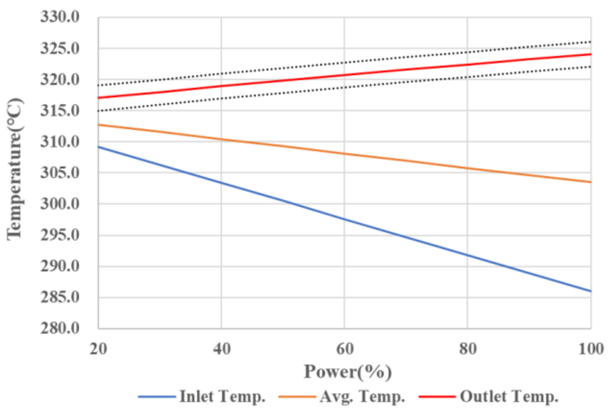

Fig. 3 RCS Temperature Program of i-SMR

The key procedure of reactivity control simulation during power change in this study is as follows. First, a critical core calculation is performed using the inlet temperature corresponding to the target core power as an input condition, based on the RCS temperature program. Here, this study assumes that the inlet temperature at the target power, as specified by the RCS temperature program, can be achieved through specific thermal interactions with the secondary system, regardless of perturbations in the outlet temperature. Changing the core power involves the total power defect, which includes Doppler feedback and the reactivity change caused by the gradual variation of xenon concentration with core power. If the reactivity insertion caused by this inlet temperature sufficiently compensates for the power defect required to achieve the target power, the predicted critical core power will be close to the target power. Whether the target power is reached is determined using an outlet temperature-based reactivity control method, which, as mentioned earlier, is directly influenced by the calculated core power. If the outlet temperature deviates from the preset range for each power level, the calculation is iteratively performed to determine the control rod position that achieves criticality under the target power conditions.

In this study, core simulation calculations were performed for daily load-following operations under 100-50-100% and 100-20-100% power change, using a time-based schedule of 2-4-2-16 hour as a representative example of flexible operation. The analysis focuses on carrying out at the beginning-of-cycle (BOC) and end-of-cycle (EOC) for the initial core of the i-SMR.

3. Results

Figures 4 to 7 illustrate the behavior of the outlet temperature and the lead bank(R4) over 48 hours during reactivity control in daily load-following operations for each power variation condition of 100-50-100% and 100-20-100%.

According to the results, the outlet temperature behavior at the BOC and EOC is similar for both power change cases, indicating that the control rods also move at similar times and magnitudes.

Additionally, as the power variation range increases, more control rod movement is required. This can be understood as a result of differences in the dynamic changes in xenon concentration caused by power fluctuations.

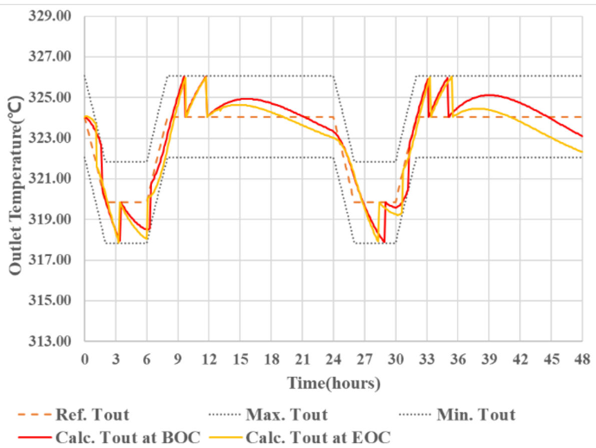

Fig. 4 Behavior of Outlet Temperature for 100-50-100% Daily Load-follow Operation

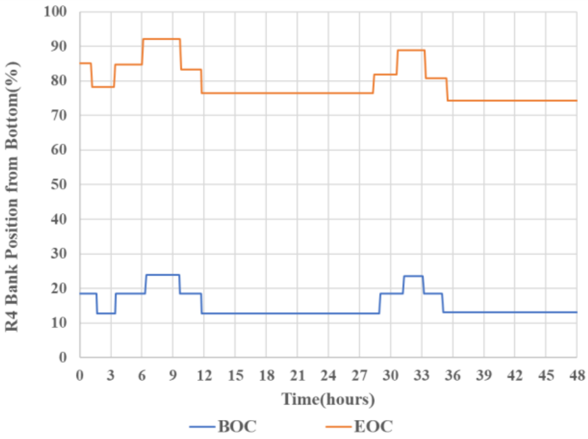

Fig. 5 Behavior of R4 Bank Position for 100-50-100% Daily Load-follow Operation

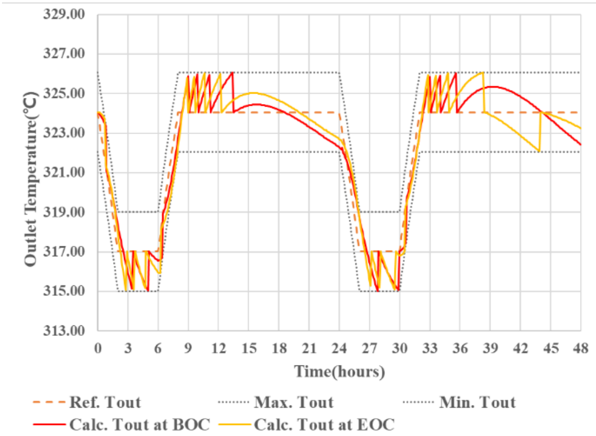

Fig.6 Behavior of Outlet Temperature for 100-20-100% Daily Load-follow Operation

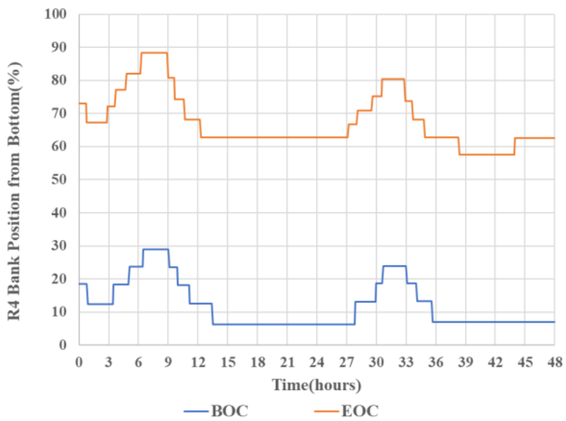

Fig. 7 Behavior of R4 Bank Position for 100-20-100% Daily Load-follow Operation

Table I contains the comparison result of change in the maximum peaking factors (F_r and F_q) between before and during daily load-following simulation with control rod operation based on the outlet temperature control.

Table I: Summary of the Peaking Factors for Load-following Simulation

Case		Pre		Post	
		F_r	F_q	F_r	F_q
100-50-100%	BOC	1.474	2.176	1.509	2.266
	EOC	1.411	2.110	1.443	2.202
100-20-100%	BOC	1.474	2.176	1.534	2.319
	EOC	1.411	2.110	1.417	2.265

The results indicate that for specified daily load-following case, Fr increases by up to 4.1% and Fq increases by up to 7.3%.

The results in Table II show that for 100-50-100 daily load-following operation, the control rods moved up to 4.5 times per day with a total distance of approximately 76.1 cm. For 100-20-100 operation, the movement reached up to 9.0 times per day with a total distance of 117.6 cm. Additionally, it can be confirmed that the daily average distance and frequency of control rod movement tend to increase as the magnitude of power change becomes larger.

Table II: Summary of the Frequency and Total Travel Length for Load-following Simulation

Case		Average per Day	
		Frequency	Total Travel Length(cm)
100-50-100%	BOC	4.5	58.6
	EOC	4.5	76.1
100-20-100%	BOC	7.0	95.4
	EOC	9.0	117.6

4. Conclusions

In this paper, in order to confirm the capability of the control rod operation for reactivity control derived by the combination of a very large negative MTC and an appropriate RCS temperature program in the i-SMR, a simulation analysis of the daily load-following operation using a control rod operation method based on outlet temperature was conducted.

As the result of the simulation of daily load-following operations for each power variation case of 100-50-100% and 100-20-100%, the total peaking factors showed a maximum increase of approximately 7% and the maximum daily control rod movement was evaluated to be 117.6 cm per day.

In the future, this study plans to further conduct simulation calculations of outlet temperature-based control rod operation method for various i-SMR core conditions and daily load-following scenarios. Based on these analyses, a quantitative evaluation of the mitigating effect on control rod movement induced by this method will be performed.

Acknowledgement

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