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The Feasibility of Controlling Secondary Reactivity Based on Coolant Temperature for Soluble Boron-free Operation

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1. Introduction

Innovative-Small Modular Reactor (i-SMR), which is an integral type pressurized water reactor designed for small scale of power currently under development, considers soluble boron-free operation as one of its top requirements.

Generally, a soluble boron-free core has a strongly negative moderator temperature coefficient (MTC), which accounts for a high sensitiveness of the moderator (coolant) temperature to the reactivity in the soluble boron-free core.

General Design Criterion 26 in 10CFR50 Appendix A states that the reactor must have not only control rods but also the other independent reactivity control system with different design principle such as soluble boron in the conventional nuclear power plants [1]. In this respect, the i-SMR would introduce a method of intentionally changing the coolant temperature which results in the considerable reactivity feedback derived by the very negative MTC for a soluble boron-free core as a secondary reactivity control system.

This study is designed to preliminarily investigate a feasibility of the secondary reactivity control system for the i-SMR using the coolant temperature change in terms of core physics and thus focuses on demonstrating whether the core power and reactivity can be sufficiently well-controlled corresponding to the coolant temperature changes.

Since this paper is only interested in the nuclear impact to the core, mechanical or thermal-hydraulic effects on entire nuclear systems, including the secondary system, are considered beyond the scope of this study. Additionally, it is assumed that the coolant temperature could be precisely changed regardless of the practical coolant temperature control capability of the secondary system.

In this paper, in order to simply identify the capability of controlling the core reactivity by coolant temperature change, a behavior of coolant temperature to control the total excess reactivity for normal operation was analyzed and also a quantitative understanding of the reactivity variation due to power change in the i-SMR was involved. In addition, simulations for several sample cases under normal operating conditions including planned power changes such as daily load follow were conducted.

2. Methods and Results

2.1 Computational methods

A unit assembly depletions for two groups cross section generation were performed by KARMA (Kernel Analyzer by Ray-tracing Method for fuel Assembly) [2,3] 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. For whole core calculation, ASTRA code was used [4]. 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) [5,6].

2.2 Total excess reactivity control by only coolant temperature

At first, it was examined how much change of coolant temperature is required so as to control the total excess reactivity of the i-SMR core without a contribution of control rods throughout the cycle.

The calculation was performed over the entire burnup range of initial cycle for the i-SMR by searching for the inlet temperature condition that makes the core critical with all control rods fully withdrawn.

Fig. 1 confirms that the maximum increase of 13.5 degrees Celsius in the inlet temperature and 12.2 degrees Celsius in the average temperature are needed to manage the total excess reactivity by only changing the coolant temperature, while the ASI remains relatively stable.

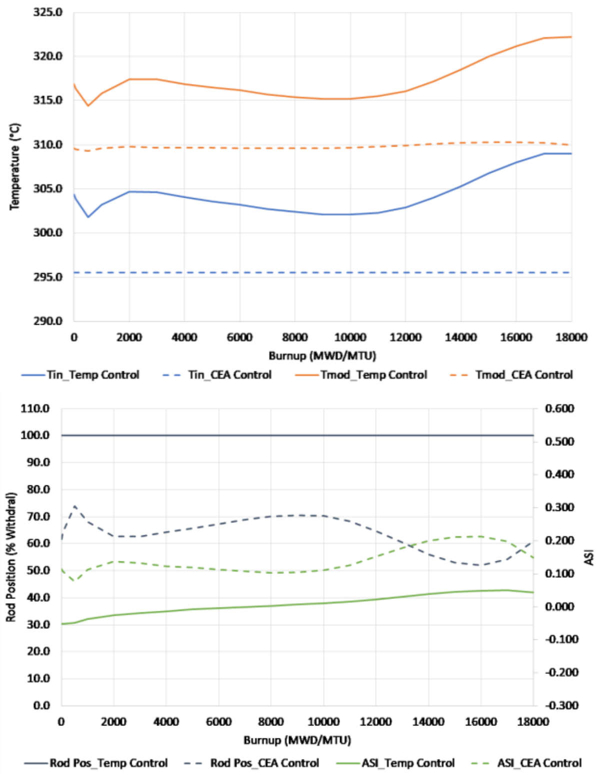

Fig. 1 Control of excess reactivity by only changing coolant temperature over the initial cycle

2.3 Componential analysis of reactivity variation due to power change

A change in core power results in the corresponding changes in thermal and neutron flux distribution, which causes the reactivity variation due to changes in xenon concentration as well as the power defect that is a combined feedback effect due to moderator and fuel temperature changes.

In order to figure out the effect on reactivity due to power change, componential reactivity calculation (by power defect and xenon reactivity) were performed for one of daily power changing condition (100-20-100%, 2-4-2-16 hours). This evaluation was carried out at the condition with control rods fixed for initial critical state, calculating the eigenvalues for each power changing with time.

Prior to this calculation, it is necessary to consider the RCS temperature program to establish the coolant temperature corresponding to the core power. If the average coolant temperature increases with increasing power, as is the case in most commercial soluble boron plants, soluble boron-free core with a very strong negative MTC would result in significantly larger power defects, making core power changes more difficult. Therefore, in order to relieve the adverse effect, it seems desirable to use a curve in which the average coolant temperature slightly decreases linearly as the power increases for soluble boron-free core. For the i-SMR, RCS temperature program has not been determined yet. In this study, the RCS temperature program is assumed as shown in Fig. 2.

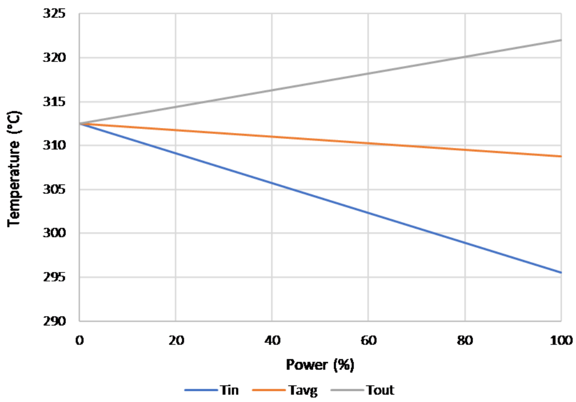

Fig. 2 i-SMR RCS temperature program

Fig. 3 shows that the net change of reactivity with the power change is estimated to be in a range of +290 pcm to -190 pcm. This results from the combination of the positive effect on reactivity of up to 480 pcm due to the power defect and the negative effect of up to 400 pcm due to the burnout of xenon.

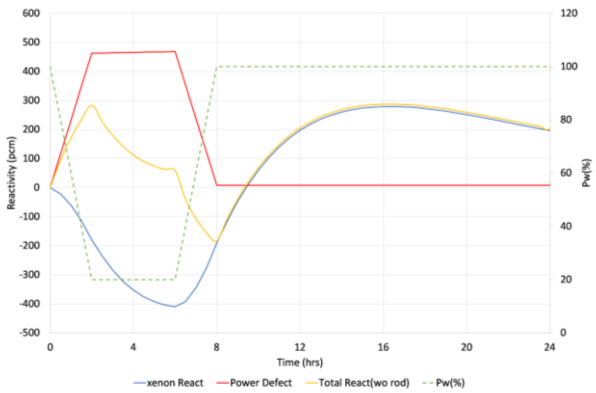

Fig. 3 The reactivity variation with power change (100-20-100%)

As noted above, a change of the core power immediately makes the fuel and coolant temperature vary with the power, causing a positive or negative reactivity insertion, so-called ‘power defect’. Therefore, it is reasonable to use an Isothermal Temperature Coefficient (ITC), which accounts for a comprehensive effect on reactivity due to the fuel and coolant temperature change, in considering the reactivity variance required for the power change.

Table. I contains the ITC at BOC of the initial cycle for the i-SMR and Temp./pcm. Temp./pcm is defined as the inverse of ITC. Dividing the corresponding reactivity change by this parameter could provide a rough estimate of the range of coolant temperature required to make up for the reactivity. In that power change case, it can be expected that the temperature increase of up to about 5.8°C sufficiently regulates the reactivity variation caused by power change.

Table I: Reactivity coefficient for 1st cycle BOC

ITC [pcm/°C]	Temp. /pcm [°C/pcm]
-66.18	-0.02

2.4 Daily load follow control for soluble boron-free core

In this section, 3 representative cases of the daily load follow control are addressed. In each case, power is decreased from 100% of rated power to the target level (20%, 50% and 75%) for 2 hours and held for 4 hours, then returned to 100% for 2 hours and held for 16 hours. For these simulations, the procedure was performed in each case to find the inlet temperature required to maintain the core to be critical under power changing condition while the control rods are held at the initial critical position.

The calculations showed that in all cases, a more rapid temperature change than the coolant temperature change specified by the RCS temperature program is required to change the core power, which is due to the Doppler feedback effect not being sufficiently canceled out. After the power decrease, the decreasing trend in the required average coolant temperature while the power remains constant is due to the negative reactivity insertion caused by the temporary increase in xenon concentration resulting from the decrease in neutron flux, and the increasing trend in the required average coolant temperature after the power increase can be also explained with the same manner.

Fig. 4 shows that the variations of inlet temperature and average temperature from the programmed temperatures are in a range of ±5.6°C for the daily load follow control with 20% power operation.

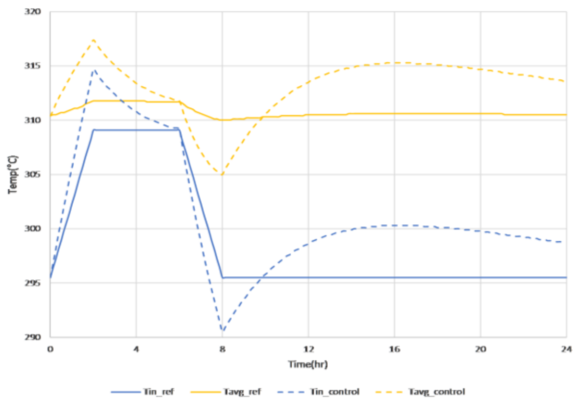

Fig. 4 Daily load follow with temperature control (100-20-100%)

Fig. 5 shows that the additional changes of ±3.3°C in inlet temperature and average temperature are required for daily load follow control with 50% power operation.

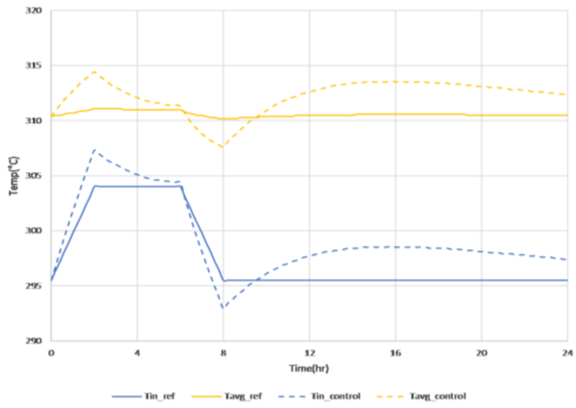

Fig. 5 Daily load follow with temperature control (100-50-100%)

Fig. 6 indicates that, in case of the daily load follow with 75% power operation, the reactivity control could be achieved by varying the inlet temperature and average temperature within ±1.5°C.

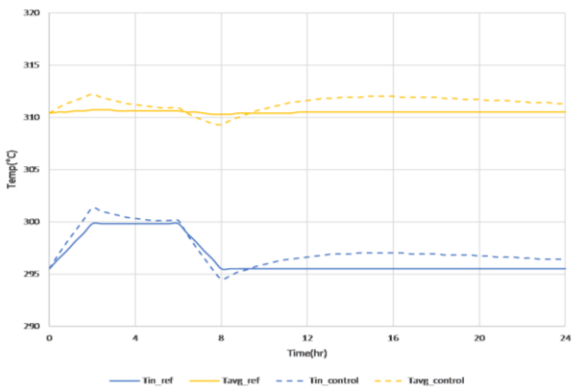

Fig. 6 Daily load follow with temperature control (100-75-100%)

3. Conclusions

This paper addressed whether core power and the corresponding reactivity change could be managed by only using the coolant temperature control for the i-SMR, soluble boron-free core with the strongly negative MTC. For these analyses, 3 cases of daily load follow were simulated.

From the results, it was confirmed that a more rapid change in coolant temperature was required to compensate for the change in reactivity contributed by the change in xenon concentration, in addition to the relatively stronger Doppler feedback effect for change in core power.

In the case of the daily load follow of 100-75-100%, it was found that the coolant temperature range within ±1.5 °C could be available for reactivity control.

In the future, further studies on the possibility of secondary reactivity control system will be conducted not only in the equilibrium core but also in various other conditions.

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