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Applicability of Existing Pressurizer Pressure Control Logics for Load-Following Operation of PWR-type SMR Using MTC-Based Secondary Reactivity Control

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1. Introduction

Nuclear power plants are increasingly being called upon to operate in load-following modes to accommodate the intermittent nature of renewable energy sources and fluctuating grid demands. This shift presents unique challenges for small modular reactors (SMRs), which are designed to be more flexible and economical than traditional large-scale reactors. One promising approach for enabling load-following in SMRs is the use of moderator temperature coefficient (MTC)-based secondary reactivity control, which leverages the inherent physics of the reactor core to adjust power output.

The innovative SMR (i-SMR), a pressurized water reactor (PWR)-type SMR that is the focus of this study, adopts a soluble boron-free design and a strongly negative MTC. In such reactors, changing the thermal-hydraulic conditions of the secondary system can induce temperature variations in the reactor coolant, ultimately enabling reactivity control. Thus, it is important to quantitatively analyze the feasibility of using MTC-based secondary reactivity control for load-following operation. In this light, this study aims to examine how quickly and to what extent power can be altered using only MTC as a secondary reactivity control method.

However, altering the secondary-side thermal-hydraulic conditions can cause significant transients in the primary side. To maintain stability during these transient conditions, this research primarily utilizes pressurizer pressure control system (PPCS) logic from commercial nuclear power plants as the pressure control method. Together with the feasibility of MTC-based reactivity control, this study examines whether adapting existing PPCS logic can effectively manage transient situations in the i-SMR context. To explore this, this study focuses on the dynamics of pressurizer pressure during load changes, considering the unique core physics of the soluble boron-free i-SMR.

Ultimately, this research lays the groundwork for advanced load-following strategies in SMRs by demonstrating how MTC-based secondary reactivity control, supported by existing PPCS logic, can enable flexible and safe nuclear power generation in response to dynamic grid demands.

2. Methodology

2.1 Description of i-SMR

The reference reactor used in this study is the i-SMR with a thermal capacity of approximately 520 MWt. The design characteristics of i-SMR is summarized in Table I. While it follows most features of a large commercial PWR, it adopts a helical once-through type steam generator (SG).

Table I: Design characteristics of i-SMR

Reactor type	Integral PWR
Thermal/electrical capacity per reactor [MWt/MWe]	520/170
NSSS operating pressure [MPa]	15.5
Core inlet/outlet coolant temperature [°C]	286.0/321.0
Steam generator	Helical once-through type

In this study, a MARS-KS input file for simulating the i-SMR was developed (see Fig. 1). The primary side was modeled as a closed loop, while the secondary side was modeled as an open loop. The primary side flow rate was maintained by the reactor coolant pump (RCP). For the secondary side, time-dependent junctions (TMDPJUN) and volumes (TMDPVOL) were used to maintain the feedwater flow rate and the turbine inlet pressure. The i-SMR SG consists of more than 5,000 heat transfer tubes, categorized into more than 20 layers based on coil diameter and angle. However, this study basically modeled the SG as a group of 4 units.

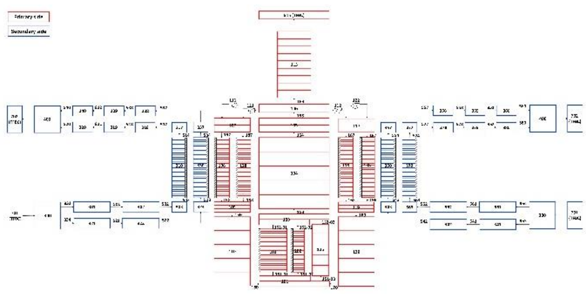

Fig. 1. MARS-KS nodalization of i-SMR.

The i-SMR core is modeled using the point kinetics module in MARS-KS [2]. By applying the moderator density vs. reactivity table corresponding to the i-SMR core design, the reactivity feedback effects in response to RCS temperature changes can be simulated.

2.2 Operating conditions under load-following

The i-SMR targets a 100-20-100% load-following cycle. Table II summarizes the secondary-side coupling conditions for each output, with all values normalized to 100% power. In this study, the primary-side variations are observed as the secondary conditions are adjusted according to Table II during load-following. In MARS-KS code, the secondary side conditions can be adjusted by manipulating the TMDPJUN and TMDPVOL. Two scenarios—100-50-100% and 100-25-100%—are simulated with ramp rates of 0.25%/min and 0.5%/min, respectively. By calculating these four cases, the study aims to evaluate the stability of MTC-based reactivity control without control rods.

Table II: Normalized TH conditions of the secondary side at various power levels (FW=feedwater, MS=main steam)

Power level [%]	FW mass flow rate	FW temperature	MS temperature	MS pressure
20	0.179	0.917	1.045	1.181
25	0.225	0.922	1.046	1.170
50	0.459	0.948	1.048	1.118
75	0.706	0.973	1.045	1.067
100	1.000	1.000	1.000	1.000

2.3 Pressurizer pressure control logic

As described in Section 2.2, the study varies the secondary conditions over time to alter the reactor power. Without proper control measures, this induces significant transients on the primary side that may push the system beyond the limiting condition for operation (LCO). One of the basic NSSS control systems for the primary side is the Pressurizer Pressure Control System (PPCS), which regulates pressure using heaters and sprays. Since the control logic for all NSSS control systems in the i-SMR has not yet been established, an arbitrary PPCS is modeled to control only the primary pressure. Proper control of the primary pressure is expected to maintain the RCS temperature and flow rate within acceptable limits.

In this study, a hypothetical PPCS was modeled, assuming a proportional heater and a spray system [3]. The spray system was designed to draw water from the cold leg, similar to conventional nuclear power plants. The heater output increases as the pressurizer pressure decreases, while the spray valve area expands with rising pressure. The pressure-dependent control strategies for the heater and spray are illustrated in Fig. 2.

To simulate the heater, a heat structure was attached to the lower portion of the pressurizer to supply power. For the spray, a pipe was installed between the cold leg and the top of the pressurizer, connecting them with a servo valve. The servo valve can adjust its opening according to the control logic described in Fig. 2.

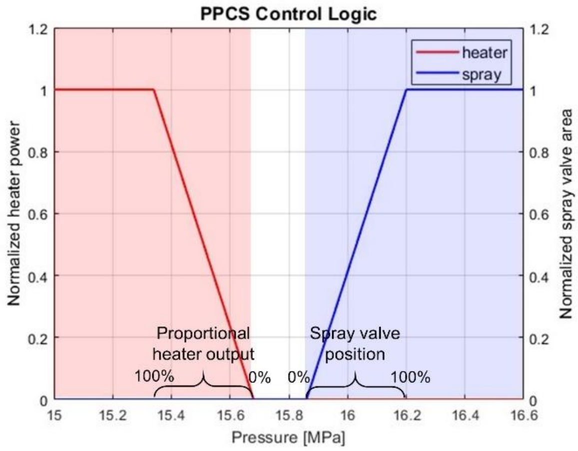

Fig. 2. PPCS control logic. The red-shaded region denotes the heater's operating zone, while the blue-shaded region denotes the spray's operating zone.

3. Results and Discussions

In this section, the results of MARS-KS code calculations under two load variation scenarios with two different ramp rates are shown. The analysis focuses on whether the reactor power accurately follows the target reactor power even in the absence of control rods and whether the pressurizer pressure is properly maintained by the postulated PPCS.

3.1 Load-following operation of 100-50-100%

This section examines a scenario where the output starts at 100% and is reduced to 50%, then returning to 100%. The results, using ramp rates of 0.25%/min and 0.5%/min, are presented in Figs. 3 to 6. As shown in Fig. 3, both cases effectively track the target power; however, higher oscillations are observed in the case with the faster ramp rate. Notably, significant oscillations occurred around the points where the power reduction and subsequent increase were completed.

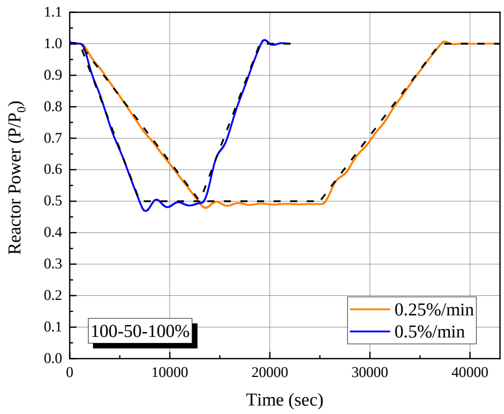

Fig. 3. Reactor power vs. time under 100-50-100% load-following operation with different ramp rates. The black dashed lines denote the target reactor power value.

Fig. 4 shows the trend of pressurizer pressure for both cases. In this figure, the upper setpoint indicates the pressure at which the spray reaches 100% opening, while the lower setpoint indicates the pressure at which the proportional heater output reaches 100%. The results indicate that the pressure remains between 15.5 MPa and 15.8 MPa throughout the simulation. The degree of pressure oscillation was similar in both ramp rates.

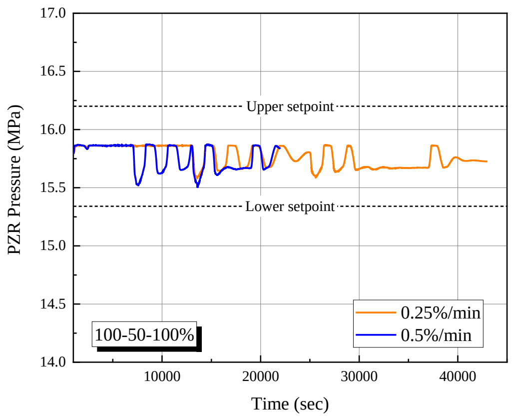

Fig. 4. Pressurizer pressure vs. time under 100-50-100% load-following operation with different ramp rates.

Figs. 5 and 6 show the operational history of the PPCS for ramp rates of 0.25%/min and 0.5%/min, respectively. Since the y-axis scales of both graphs are the same, heater power and spray flow can be directly compared. During the power reduction phase, the spray operation dominated, as the decrease in secondary flow reduced the heat exchange through the steam generator, causing the spray to activate to cool the primary side. Conversely, during the power increase phase, the heat exchange increased, leading to excessive cooling of the primary side, thus requiring a rapid increase in heater power. Generally, the faster ramp rate cases showed higher heater power and spray flow, indicating that the PPCS intervened more to stabilize the pressure in response to rapid system changes.

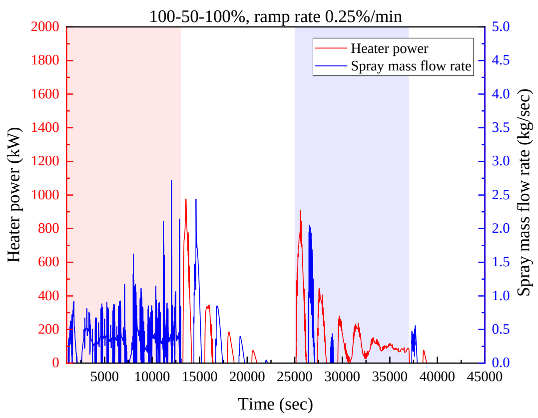

Fig. 5. PPCS operation vs. time under 100-50-100% load-following operation with ramp rate of 0.25%/min. The red-shaded region denotes the ramp-down zone, while the blue-shaded region denotes the ramp-up zone (same for Figs. 6, 9, 10).

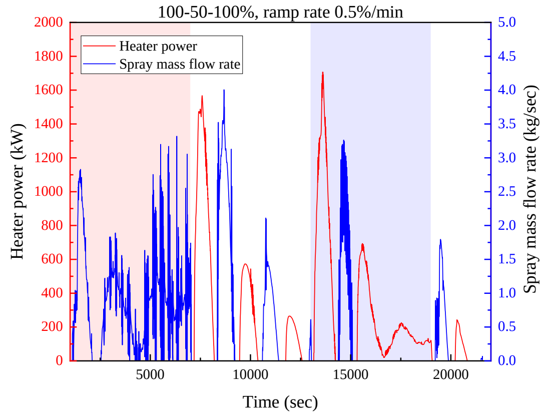

Fig. 6. PPCS operation vs. time under 100-50-100% load-following operation with ramp rate of 0.5%/min.

3.2 Load-following operation of 100-25-100%

This section addresses the scenario in which the output is reduced to 25% and then returned to 100%. Fig. 7 shows the reactor power changes for both ramp rates. Again, the target output is well tracked, but the oscillation of the output was more pronounced compared to the 100–50–100% scenario.

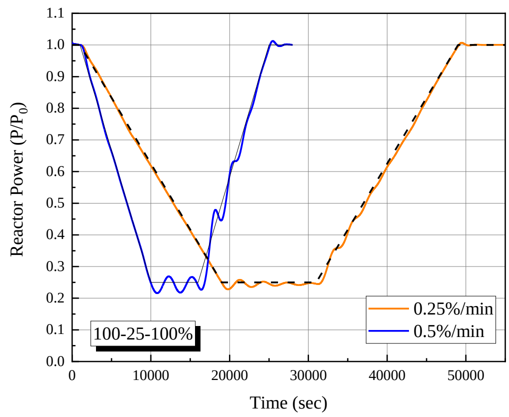

Fig. 7. Reactor power vs. time under 100-25-100% load-following operation with different ramp rates. The black dashed lines denote the target reactor power value.

Fig. 8 shows the changes in pressurizer pressure. In the 0.25%/min case, the pressure remained within the upper and lower setpoints, while the 0.5%/min case exhibited significant oscillations beyond these setpoints. In other words, although the core power output eventually reached the target value, the pressure exceeded its limits.

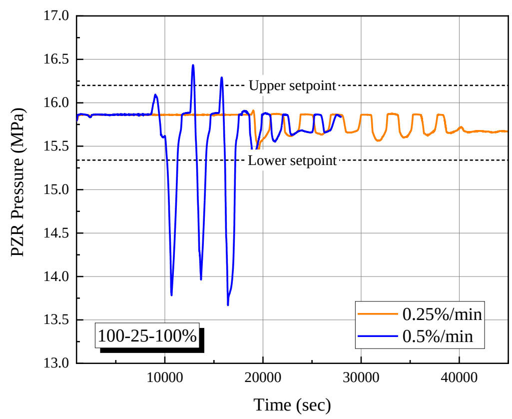

Fig. 8. Pressurizer pressure vs. time under 100-25-100% load-following operation with different ramp rates.

Fig. 9 and Fig. 10 present the operating history of the PPCS for ramp rates of 0.25%/min and 0.5%/min, respectively. Compared to the 100-50-100% scenario, significantly higher heater and spray activity is observed. In the faster ramp rate case, the spray system reached 100% opening, and due to the large pressure difference between the cold leg and the pressurizer, the spray flow rate increased substantially. The proportional heater output also spiked to its maximum capacity.

These effects were particularly pronounced at the end of the power reduction phase, as secondary-side control ceased before the energy balance between the primary and secondary sides was fully stabilized. Even after the change in secondary-side stopped, thermal inertia caused the primary side to further converge toward overcooling.

Since this study attempted to control this transient behavior using only heaters and spray, there were limitations. However, if additional NSSS control systems, such as a pressurizer level control system, were incorporated, it may be possible to maintain the system within operational limits.

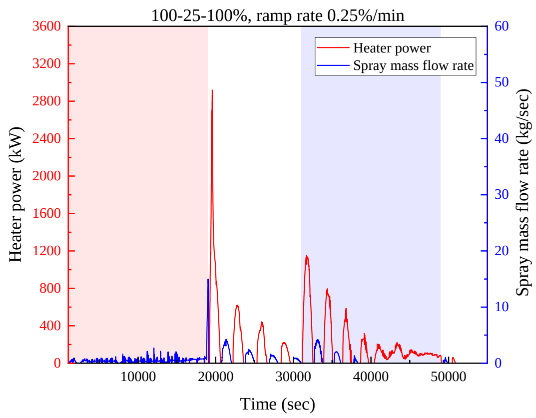

Fig. 9. PPCS operation vs. time under 100-25-100% load-following operation with ramp rate of 0.25%/min.

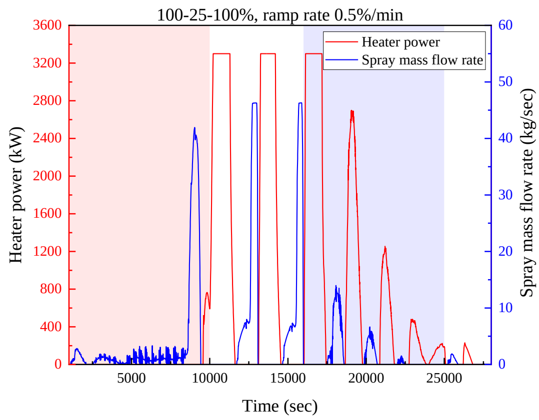

Fig. 10. PPCS operation vs. time under 100-25-100% load-following operation with ramp rate of 0.5%/min.

4. Conclusions

This study evaluated a PWR-type SMR's load-following capability with a large negative MTC by achieving target outputs (50% and 25%) solely through secondary-side thermal-hydraulic variations. Two scenarios (100-50-100 and 100-25-100) were tested at ramp rates of 0.25%/min and 0.50%/min, with pressurizer pressure controlled via heater and spray. Results confirmed that desired outputs were attainable, indicating that secondary-side changes can modulate reactor power without the use of control rods or CVCS. However, higher ramp rates increased heater and spray activity, causing larger fluctuations.

Limitations include the simplified point kinetics analysis in MARS-KS, arbitrarily defined heater and spray capacities, and the omission of control strategies for feedwater and main steam lines. Future studies should develop control strategies for various control systems, including the PPCS, and assess their sensitivities.

ACKNOWLEDGMENT

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