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Preliminary Evaluation of Core Monitoring Performance and TM-ICI for Soluble-Boron-Free Small Modular Reactor

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1. Introduction

In the commercial pressurized water reactors (PWRs), the in-core instrumentation (ICI) system provides input signals to monitor the safety parameters. Each ICI consists of five neutron detectors and one core exit thermocouple. The local neutron signals from ICIs are used to synthesize the entire core power distributions and monitor that the departure from nucleate boiling ratio (DNBR) and the peak linear heat rate are within the design limits [1]. It is noted that ICI cables penetrate through the bottom nozzles of the reactor vessel in the commercial PWRs in Korea.

In the small modular reactor (SMR), the top-mounted ICI (TM-ICI) design is considered to eliminate the bottom penetration of the ICI cable and prevent the leakage of the corium during the severe accident [2]. However, the TM-ICI cannot be installed at the fuel assemblies, where the control element drive mechanisms (CEDMs) are located. Furthermore, a large number of CEDMs is required to guarantee the subcriticality at the cold zero power (CZP) condition due to a large negative moderator temperature coefficient (MTC) in the soluble-boron-free SMR. These issues restrict the total number of ICIs in the soluble-boron-free SMR and require a proper arrangement of ICIs and an improved core monitoring system.

This paper is to evaluate the core monitoring performance of the TM-ICI design for the soluble-boron-free SMR. The two-step core analysis code STREAM/RAST-K [3] is used to simulate a typical SMR core design. Several core monitoring parameters such as the core average power, the axial power shape, and the quadrant power tilt rate (QPTR) are compared with those of the commercial PWR to assess the feasibility of the TM-ICI in the soluble-boron-free SMR.

2. Methods and Results

2.1 Methods

The soluble-boron-free SMR model in this study consists of 69 fuel assemblies (FAs) with 17x17 fuel lattice and is designed to generate 540MWth. The 20 ICIs are installed at the same position in the quarter symmetry. The ICI ratio for FA is 29%. In the core of the typical commercial PWR, is equipped with 45 ICIs, 25% of 177 FAs. The commercial PWR has four pairs of symmetric ICI groups each consisting of 9 ICIs. Each quadrant of core has 10 to 12 ICIs and there are incompletely symmetric configurations.

The ICI must maintain core monitoring performance under the limited operating conditions. The in-core detector system shall satisfy that at least 75% of the ICIs are operable [4]. To satisfy this regulation, the evaluation of ICI was conducted under various conditions, including the ICI being intact or partially failed.

The RAST-K calculation results provided core monitoring parameters. The monitoring parameters used in the evaluation were average power, axial power distribution, and $\mathrm{QPTR}_{\mathrm{ICI}}$. The axial power distribution of ICI positions is assumed that completely reconstructed. $\mathrm{QPTR}_{\mathrm{ICI}}$ is can be obtained as

$$QPTR_{ICI} = \frac{\max(\overline{P_Q})}{P_{avg}} \tag{1}$$

The average core of entire power P_{avg} and quadrant core power $\overline{P_Q}$ are defined as

$$P_{avg} = \frac{\sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} w_i} \tag{2}$$

$$\overline{P_Q} = \frac{\sum_{i\in Q} P_i}{\sum_{i\in Q} w_i} \tag{3}$$

where N denotes number of nodes, 1 FA has 4 nodes and w_i is 0.25.

The monitoring parameter error is absolute difference between the value of the ICI installation locations and the entire FA locations. It evaluated the monitoring performance of the SMR compared to the commercial PWR. The core simulation was performed from beginning of cycle (BOC) to end of cycle (EOC). The monitoring parameter errors were calculated every 1000 MWD/MTU to consider trend in burnup. To compare the QPTR monitoring performance between the SMR and the commercial PWR cases in the power tilt condition, a control rod bank in the second quadrant of the core was inserted at the specific burnup step (BOC, MOC, and EOC) to induce $\mathrm{QPTR}_{\mathrm{ICI}}$ 1.02 in both cases.

2.2 Results at operating condition with intact ICIs

The average and maximum errors in all burnup steps were used for the assessment (Table 1). The average power error and the axial power shape error of the SMR are around 1% bigger than those of the commercial PWR. The SMR has a small $\mathrm{QPTR}_{\mathrm{ICI}}$ error due to the completely symmetry ICI configuration. Figure 1 shows that both reactor types can be monitor axial power shapes accurately under several burnup cycles.

Table 1. Errors of monitoring parameters occurred at operating condition with intact ICIs

		Commercial PWR	SMR
Average Power Error	Max.	2.03%	3.48%
	Avg.	1.80%	2.85%
Axial Power Shape RMS Error	Max.	0.78%	1.47%
	Avg.	0.56%	1.23%
$QPTR_{ICI}$ Error	Max.	4.61%	0.19%
	Avg.	4.17%	0.18%

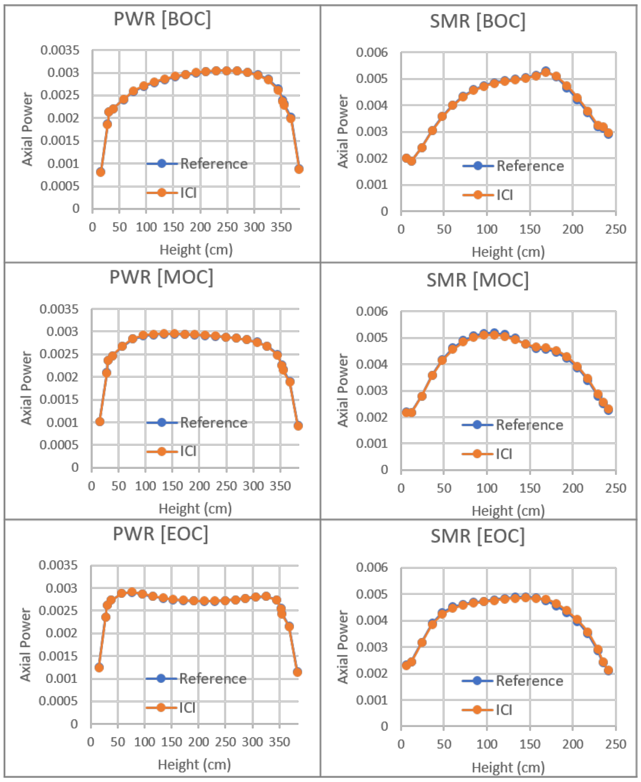

Figure 1. Axial power shapes of intact ICIs comparing to the entire core (BOC, MOC, EOC)

2.3 Results at operating condition with 25% inoperable ICIs

For verifying the monitoring system is operable with 75% of ICIs, it was assumed that commercial PWR with 45 ICIs had 11 inoperable ICIs and SMR with 20 ICIs had 5 inoperable ICIs. The 70 cases of inoperable ICIs were independently random sampled. According to the central limit theorem, the sample distribution of 70 samples means is close to the normal distribution. The monitoring parameters were evaluated by statistical analysis using approximating samples to normal distribution. The range of $\bar{X} \pm 3\sigma$ of samples with normal distribution include 99.7% of data, consider $\bar{X} + 3\sigma$ was as the maximum error. ($\bar{X}$: sample mean, σ : standard deviation)

When 25% of ICIs were failed, the SMR showed a similar tendency with increasing errors of the commercial PWR (Table 2,3). The worst axial power shape error of the commercial PWR was 1.33% and that of the SMR was 2.67%. The axial power shape errors did not significantly increase compared to the case with intact ICI, shown in Figure 2. The $QPTR_{ICI}$ errors differed greatly depending on the burnup or the location of the ICI, but on average, the SMR was slightly larger.

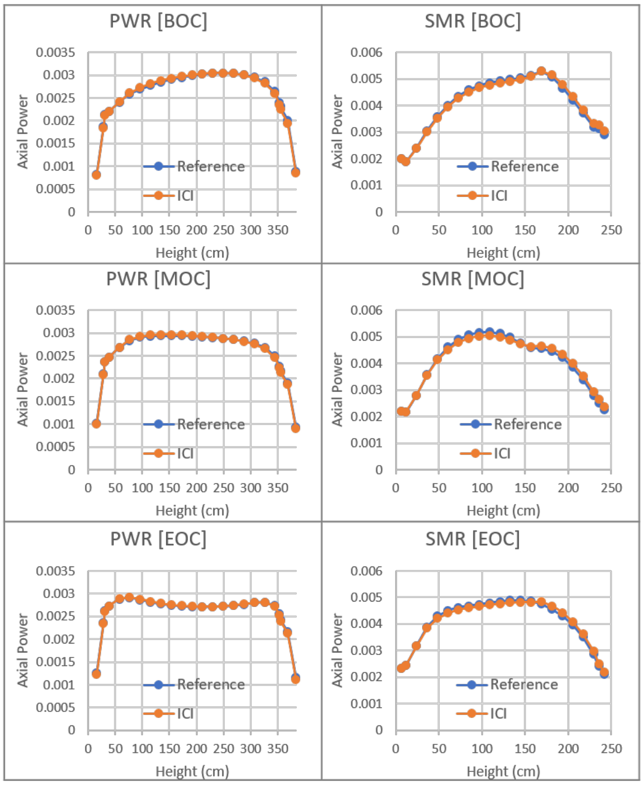

Figure 2. Axial power shapes of 25% inoperable ICIs comparing to the entire core (BOC, MOC, EOC)

Table 2. Monitoring parameter errors with 25% inoperable ICIs

		commercial PWR	SMR
Average Power Error	$\bar{X} + 3\sigma$	8.53%	9.19%
	$\bar{X}$	2.58%	3.25%
Axial Power Shape RMSE	$\bar{X} + 3\sigma$	1.33%	2.67%
	$\bar{X}$	0.60%	1.31%

Table 3. $QPTR_{ICI}$ errors with 25% inoperable ICIs

$QPTR_{ICI}$ Error		commercial PWR	I-SMR
BOC	$\bar{X}+3\sigma$	14.67%	13.05%
	$\bar{X}$	7.52%	4.47%
MOC	$\bar{X}+3\sigma$	10.40%	14.11%
	$\bar{X}$	4.68%	5.03%
EOC	$\bar{X}+3\sigma$	7.12%	11.95%
	$\bar{X}$	4.66%	3.59%

3. Conclusions

The preliminary evaluation of monitoring performance of TM-ICI for a typical soluble-boron-free SMR design was performed. The core monitoring parameters which are the core average power, the axial power shape and the $QPTR_{ICI}$ were compared with those of the commercial PWR.

The overall errors in core monitoring parameters of the SMR were slightly increased (around 1%) compared to those of the commercial PWR and the core average power obtained from the ICI locations overestimated the true core average power. This is due to that the 1) TM-ICI cannot be installed at the fuel assemblies where the CEDMs are located, 2) the control rod should be inserted to maintain the criticality in the soluble-boron-free SMR. However, the slightly degraded core monitoring performance of the TM-ICI can be complemented by the improved power synthesis method and the online core monitoring system. Thus, the overall core monitoring performance of the soluble-boron-free SMR will be enhanced compared to the conventional PWRs.

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