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A Sensitivity Study of Multiple SGTR at the i-SMR using SPACE Code

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1. Introduction

1.1 Background

Multiple steam generator tube rupture (MSGTR) is a design basis accident (DBA) that establishes a direct leakage path between the primary and secondary systems. In innovative small modular reactor (i-SMR), the reactor core, steam generators (SGs), and pressurizer (PZR) are integrated within a single reactor vessel (RV), passive safety systems such as the passive auxiliary feedwater system (PAFS) play a dominant role in decay heat removal. Due to this integral configuration, the thermal hydraulic response during MSGTR in an i-SMR differs significantly from that of conventional loop-type PWRs. In particular, primary depressurization, secondary side pressurization, and passive heat removal are strongly coupled through natural circulation and condensation heat transfer mechanisms. Detailed description of the MSGTR modeling approach and the overall thermal-hydraulic transient behavior for the reference case has been previously evaluated. Therefore, in this study, those modeling details and baseline transient results are not repeated and are instead reference to prior publications [1].

1.2 Objective of Study

The objective of this study is to systematically evaluate the sensitivity of MSGTR transient behavior in an i-SMR to variations in break size, break location, and the heat removal performance of PAFS. The sensitivity analysis focuses on key safety metrics, including peak cladding temperature (PCT), reactor coolant system (RCS) pressure response, secondary side pressure evolution, and primary to secondary leakage mass. By quantifying the relative influence of these parameters, this study aims to identify the dominant contributors to MSGTR safety margin, assess the robustness of passive heat removal capability, and provide technical insight into the design optimization of passive safety system in i-SMR,

It is emphasized that the purpose of this work is not re-evaluate the baseline MSGTR transient itself, but rather to determine how variations in critical design parameters affect accident progression and safety performance.

2. Description of the i-SMR

The i-SMR considered in this study is designed to enhance inherent safety and structural simplicity by adopting a fully integrated RV configuration and passive safety systems. The reactor core, SGs, pressurizer region, and reactor coolant pumps (RCPs) are housed within a single vessel, thereby eliminating large-diameter primary coolant piping, as illustrated in Figure 1. This configuration excludes the possibility of large-break loss-of-coolant accidents by design and significantly reduces primary coolant inventory depletion during primary-to-secondary leakage events such as MSGTR.

Unlike conventional loop-type PWRs, pressurization is achieved within the upper region of the RV without a dedicated pressurizer vessel. The integrated internal layout minimizes hydraulic resistance and supports stable natural circulation through short flow paths and reduced pressure losses. Under post-trip conditions, density differences between the heated core region and the relatively cooler SG region provide sufficient driving force for passive circulation [2].

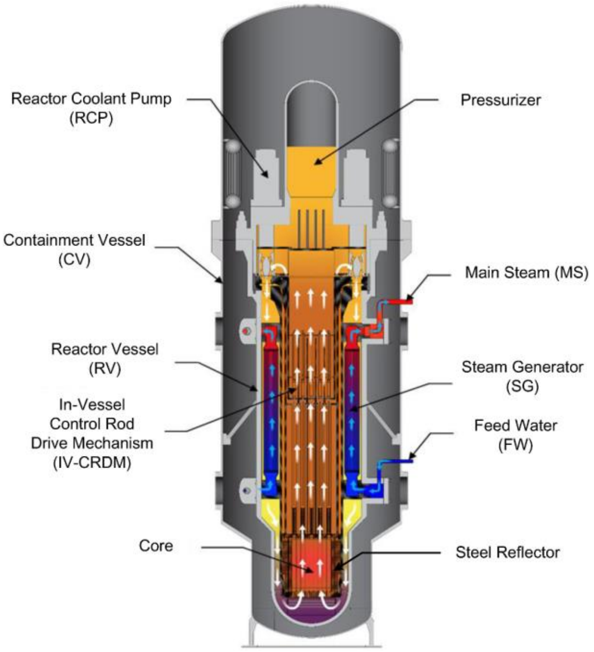

Fig. 1. Configuration of i-SMR

The i-SMR employs a compact helical-coil steam generator (HCSG) specifically optimized for integral configuration. The helically coiled tube bundles are arranged in multiple concentric layers along the annular geometry of the RV to maximize heat transfer surface area within the confined vessel volume. The secondary side is divided into multiple parallel flow paths with calibrated inlet orifices to ensure flow stability and mitigate density-wave oscillations under low-flow or high-quality conditions. Owing to the reduced mechanical loads and the equalized design pressures between primary and secondary sides, direct atmospheric release of primary coolant is inherently prevented even under MSGTR conditions. Nevertheless, to conservatively evaluate bounding safety performance, the present study assumes simultaneous rupture of multiple SG tubes.

The i-SMR relies on fully passive safety systems to accomplish decay heat removal, core cooling, and containment integrity under DBA conditions. Key systems include the PAFS, passive emergency core cooling system (PECCS), and passive containment cooling system (PCCS). These systems utilize natural circulation, gravity-driven flow, condensation heat transfer, and stored thermal energy, thereby minimizing reliance on active components, external power supplies, and operator actions. The passive heat removal capability of the PAFS is particularly relevant to the MSGTR transient response and constitutes an important parameter in the present sensitivity analysis.

3. Modeling of Multiple SGTR Sensitivity

Based on the phenomenological understanding established in the based case analysis, three parameters were selected for sensitivity evaluation: (1) the number of broken SG tubes, (2) the effective heat transfer area of the PAFS, and (3) the axial location of the broken tube. These parameters directly influence the break flow characteristics, primary-secondary pressure coupling, and passive heat removal performance, and are therefore expected to play a critical role in determining the system response during MSGTR conditions.

3.1 Break size

The number of broken SG tubes directly determines the effective break flow area and thus governs the initial depressurization rate of the RCS. To evaluate this effect, sensitivity calculations were performed by varying the number of broken tubes while maintaining the same broken location and PAFS configuration as in the bases case. The sensitivity to break size was evaluated by considering simultaneous rupture of 1,5,10, and 15 SG tubes. For each scenario, the equivalent total break area corresponding to the assumed number of broken tubes was implemented in the model to represent the cumulative break area.

3.2 Break location

The axial location of MSGTR influences the local thermal-hydraulic conditions at the break, including coolant temperature, void fraction, and driving pressure head. To assess the impact of break location, sensitivity calculations were performed by varying the axial position of the tube rupture (top, bottom) while maintaining the same number of broken tubes and PAFS configuration.

3.3 Heat transfer Area of PAFS

The heat transfer area of the PAFS directly affects the cooling ability to remove decay heat from the SGs under natural circulation conditions. To examine the sensitivity of transient response to PAFS performance, calculations were conducted with reduced and enhanced effective heat transfer areas relative to the base case.

The influence of passive heat removal capacity was evaluated by systematically reducing the heat transfer surface area of the passive condensation heat exchanger (PCHX) in the PAFS by 20%, 40%, and 60% from the reference configuration. The PCHX represents the primary heat transfer component responsible for direct condensation heat removal in the PAFS.

4. Results

The overall thermal hydraulic response of MSGTR accident in the i-SMR follows the typical sequence of primary to secondary leakage events and is briefly summarized in this study, while detailed modeling assumptions is described in research paper [1].

Following tube rupture, primary coolant leakage into the secondary side causes a rapid decrease in RCS pressure, leading to reactor trip and isolation of the main steam and feedwater lines. The secondary side pressure increases due to continuous leakage and eventually approaches equilibrium with the RCS pressure, resulting in a substantial reduction in break flow. Pressure equalization marks a key transition in the transient progression.

After reactor trip, the PAFS establishes a closed-loop natural circulation path that enables long term decay heat removal. Once the primary and secondary pressures are equilibrated, the RCS inventory is maintained and core cooling is effectively sustained by passive heat removal. During the later phase of the transient depletion of the pressurizer collapsed water level leads to rapid depressurization of both the RCS and the affected SG. However, the overall cooling performance remains sufficient, and core integrity is maintained, as shown in Figure 2. As a forementioned, a detailed description of the MSGTR modeling methodology and comprehensive thermal hydraulic results are provided in reference [1]. The present study focuses primary on parametric sensitivity evaluation.

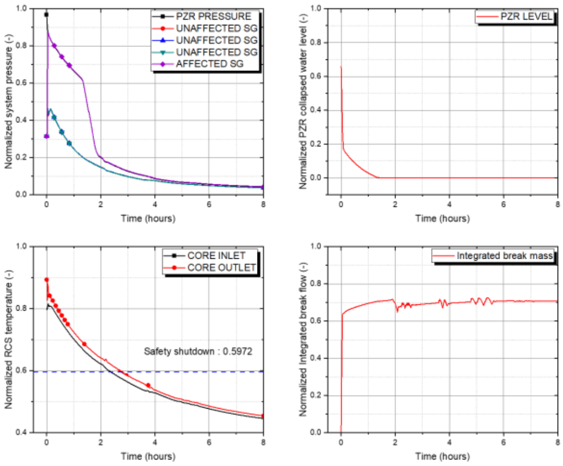

Fig. 2. Overview of MSGTR thermal hydraulic behavior

4.1 Break size

As illustrated in Figure 3 and 4, the results indicate that an increase in the number of ruptured tubes leads to a more rapid initial depressurization of the RCS, resulting in as earlier reactor trip owing to low pressurizer level. As the effective break area increases, the mass flow rate of primary coolant discharged into the secondary side increases proportionally during the early phase of the transient, as shown in Figure 5. Consequently, the secondary side pressure in the affected SG rises more rapidly, accelerating the pressure equalization process between the primary and secondary systems.

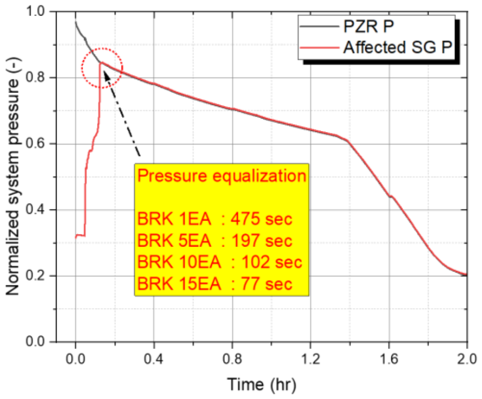

Fig. 3. System pressure equalization according to break size

Despite the differences in early transient behavior, the sensitivity results show that pressure synchronization between the RCS and the secondary system occurs in all cases once the secondary side pressure approaches the primary system pressure. After pressure equalization is established, the break flow rate decreases sharply, limiting further coolant loss. This behavior indicates that the pressure coupling mechanism identified in the base case analysis remains effective even for larger break sizes associated with multiple tube ruptures.

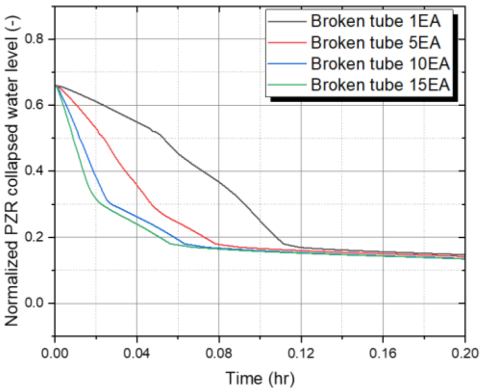

Fig. 4. Behavior of PZR collapsed water level

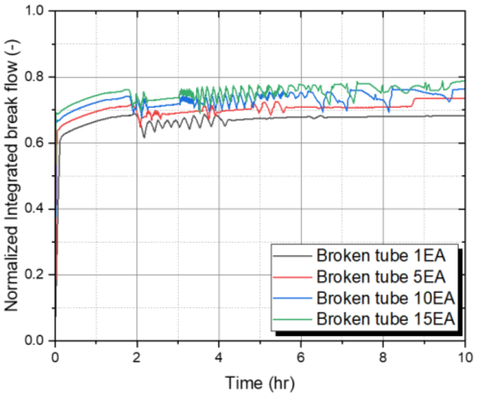

Fig. 5. Behavior of Integrated break mass

4.2 Break location

When the rupture was assumed to occur at a higher axial location within SG, the discharged coolant exhibited a higher local temperature. This resulted in a slightly increased initial break flow rate and a more rapid pressurization of the secondary side. Consequently, the pressure equalization between the primary and secondary systems was achieved earlier compared to lower break locations.

In contrast, ruptures occurring at lower axial locations were characterized by greater contribution of subcooled liquid to the break flow, resulting in a relatively slower depressurization of the RCS and delayed pressure synchronization. However, once pressure equilibrium was established, the subsequent system behavior, including coolant inventory preservation and long-term cooling performance, was largely similar across all break locations, as shown in Figure 6 and 7.

These results indicate that while the break location affects the detailed characteristics of the early transient, its influence on the long-term system response and safety relevant outcomes is limited. The dominant mitigating mechanism remains the pressure equalization between the primary and secondary systems and the sustained heat removal provided by the PAFS.

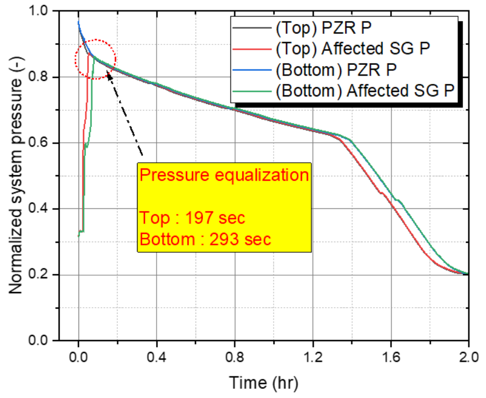

Fig. 6. System pressure according to break location

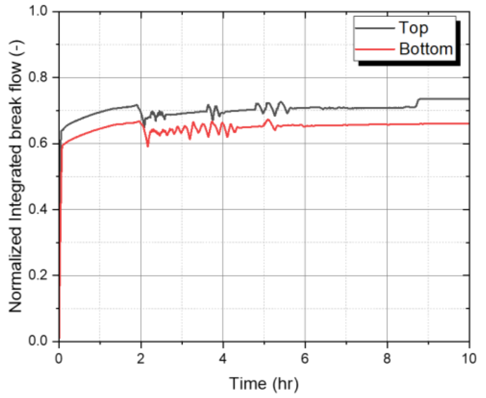

Fig. 7. Integrated break mass according to break location

4.3 Heat transfer Area of PAFS

The sensitivity results demonstrate that a reduction in PAFS heat transfer area leads to slower system depressurization during the cooling phase, due to decreased condensation and heat removal capability. As a result, the rate of secondary side depressurization following pressure equalization is reduced, slightly prolonging the duration of elevated secondary side pressure, as illustrated in Figure 8-9.

Consequently, an increase in the PAFS transfer area enhances the condensation rate in the SGs, promoting more efficient heat removal and accelerating the reduction of secondary side pressure. Despite these differences, the sensitivity analysis indicates that the overall system response is relatively insensitive to moderate variations in PAFS heat transfer area, provided that a low heat removal capacity is maintained.

In all cases analyzed, the PAFS was capable of removing decay heat sufficiently to prevent core heat up and safety shutdown criterion temperature were reached without safety issue. This result demonstrates that a substantial thermal margin is maintained in the passive cooling design.

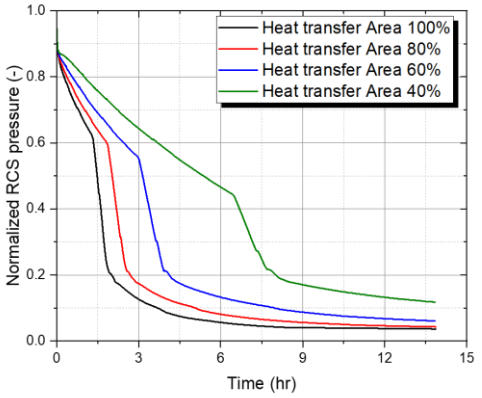

Fig. 8. RCS pressure

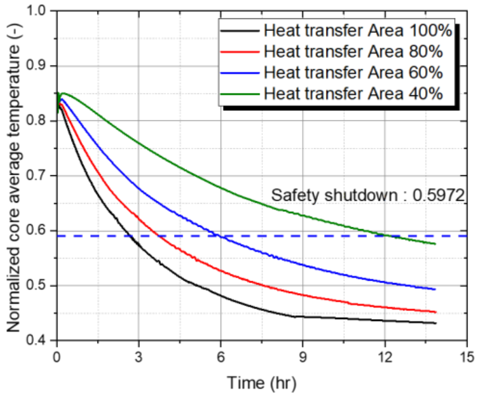

Fig. 9. Core average temperature

5. Conclusions

This study performed a systematic sensitivity evaluation of the MSGTR behavior in i-SMR, focusing on three key parameters (break size, break location, heat transfer area of PAFS). The objective was not to re-examine the baseline transient, but to quantify how variations in these parameters influence accident progression and safety relevant system responses.

Among the parameters considered, break size exerts the strongest influence on early transient behavior. An increase in the effective break area accelerates primary depressurization enhances primary to secondary discharge flow, and promotes faster pressure equalization between the RCS and the affected SG. However, once pressure synchronization is established, the break flow decreases significantly and the subsequent system response becomes relatively insensitive to further increases in break area. This confirms the dominant role of pressure coupling in limiting coolant loss during MSGTR events.

The axial location of tube rupture mainly affects the detailed characteristics of the initial discharge, including vapor quality and the timing of secondary pressurization. While higher break locations lead to slightly faster early pressure evolution, the long-term cooling behavior and overall safety metrics show minimal dependence on rupture location.

Sensitivity to PAFS heat transfer area demonstrates that reduced condensation section delays secondary side depressurization due to diminished passive heat removal capability. Nevertheless, even with a 60% reduction in effective heat transfer area, sufficient decay heat removal is maintained and core heat up is prevented. This indicates that a substantial thermal margin exists in the passive safety design.

Overall, the MSGTR response in the i-SMR is primarily governed by rapid primary-secondary pressure equalization and sustained passive heat removal through the PAFS. The results confirm that the integral configuration and passive safety systems provide robust and resilient performance against reasonable variations in break characteristics and heat transfer capacity.

ACKNOWLEDGMENTS

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