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Preliminary Analysis of Investigation on i-SMR Station Blackout Scenario Using Severe Accident System Code

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1. Introduction

Recently, Small Modular Reactors (SMRs) have attracted global attention as a promising low-carbon energy source due to their enhanced safety features, modularity, and shortened construction periods [1]. Over 70 types of SMRs, including water-cooled design such as CAREM and NuScale Power Module, as well as molten salt reactors like IMSR400 and CMSR, have been developed worldwide [2].

In Korea, i-SMR with an electric output of 170 Mwe per module is under development. The design features an integrated reactor with all major components contained within the Reactor Vessel (RV) [3]. It also incorporates helical coil steam generators and a boron-free core. The i-SMR features passive safety systems that function without operator intervention or power, thereby significantly enhancing overall safety.

The passive safety systems of i-SMR include the Passive Emergency Core Cooling System (PECCS), Passive Containment Cooling System (PCCS), and Passive Auxiliary Feedwater System (PAFS) [4]. The PECCS consists of two types of valves: Emergency Depressurization Valves (EDVs) and Emergency Recirculation Valves (ERVs). The EDVs enable the reactor to release high temperature coolants into the Containment Vessel (CV) to depressurize the RV. The ERVs prevent coolant depletion in the reactor core by reinjecting condensed coolants into the reactor core when the water level in the CV exceeds that of the RV. The PCCS includes heat exchangers designed to condensate high temperature, high pressure steam within the CV, which relieves the high internal pressure. An Emergency Cooling Tank (ECT) supplies water to these heat exchangers to remove heat generated from the core. In addition, the PAFS, installed on the main steam line system, transfers decay delivered heat from the steam generator to the ECT.

Previous safety evaluations of the i-SMR have focused on preliminary accident scenario analyses, core cooling capability assessments, and investigations into the accident mitigation performance of passive safety systems. To further ensure reliability in the safety of i-SMR, it is essential to conduct analysis that shows its safety even in the harsh condition of accident scenario. In particular, the analysis of a Station Blackout (SBO) scenario confirms that even in the absence of Alternating Current (AC) power and safety-related emergency diesel generators, the i-SMR's passive safety systems effectively mitigate the accident. Accordingly, in this study, SBO accident scenario analysis was conducted using the CINEMA code, thereby providing insight for the i-SMR accident scenarios.

2. Methodology

2.1 CINEMA input model

In this study, the accident progression was simulated using the CINEMA (Code for INtegrated severe accident Evaluation and MAnagement) developed in Korea. CINEMA consists of four sub modules: CSPACE, SACAP, SIRIUS, and MASTER. CSPACE addresses in-vessel phenomena, and SACAP models ex-vessel thermal hydraulic. SIRIUS simulates fission product behavior, and MASTER coordinates the integration of these modules [5]. For conventional nuclear power plants, the SACAP module efficiently interprets numerous ex-vessel phenomena. However, in the case of i-SMR, the behavior of the CV can be adequately interpreted by the CSPACE module because the behavior of a metal containment vessel closely resembles that within the RV. As a result, only the CSPACE module was utilized for this purpose. The CINEMA input model includes safety systems such as the PECCS, which is composed of EDVs and ERVs, along with the PCCS. Additionally, the Pressurizer Safety Valves (PSVs) located at the top of the pressurizer are modeled to open when the pressure in the pressurizer exceeds the opening setpoint and to close when it drops below the closing setpoint.

2.2 Accident Scenario

The initial event for the accident scenario considered in this study is the SBO, which is defined as the complete loss of on-site and off-site AC power. Accordingly, in this scenario, it is assumed that the reactor trip occurs immediately as the accident starts, followed by the reactor coolant pumps (RCPs) trip and main feedwater pumps (MFWPs) trip. For the PECCS, all EDVs and ERVs are assumed to be fully available when their operating conditions are met. All trains of the PCCS operate passively from the beginning of the accident owing to its inherent design feature. For a conservative evaluation, it is assumed that all trains of the PAFS fail to operate. This scenario is simulated for a period of 72 hours.

3. Results and Discussion

Table I shows the sequence of major accident events in the accident scenario. The SBO scenario was initiated at 0 seconds with an immediate reactor trip and simultaneous shutdown of the RCPS and MFWPs. This deactivation of these pumps caused a loss of cooling capability for secondary system, resulting in an increase in system pressure. **Fig. 1** shows the pressure behavior in both RV and CV for 3 hours and **Fig. 2** demonstrates the pressure behavior throughout the whole calculation period. **Fig. 3** shows the coolant discharge mass flow rate through the PSVs. Once the pressurizer pressure reached the PSV opening setpoint at about 380 seconds, high temperature steam was released to the CV. Upon reaching the closing pressure from the subsequent drop in pressurizer pressure, the PSVs were closed, causing the RV pressure to rise again. Through this repetitive process, the pressure in the CV slowly increased due to the high-temperature steam from the PSVs. However, the discharged steam was condensed by the PCCS, thereby reducing the CV pressure over time. This cycle ended as the RV pressure did not reach the PSVs opening pressure after the PECCS was activated.

Table I: Major accident events

Event	Time (hr)
Accident initiation	0
Reactor trip; RCPs and MFWPs shutdown	0
Initial PSVs opening	0.105
PECCS activation (ERV and EDV opening)	1.586
Inversion of RV and CV water levels	1.975
Flow reversal through the ERVs	2.392

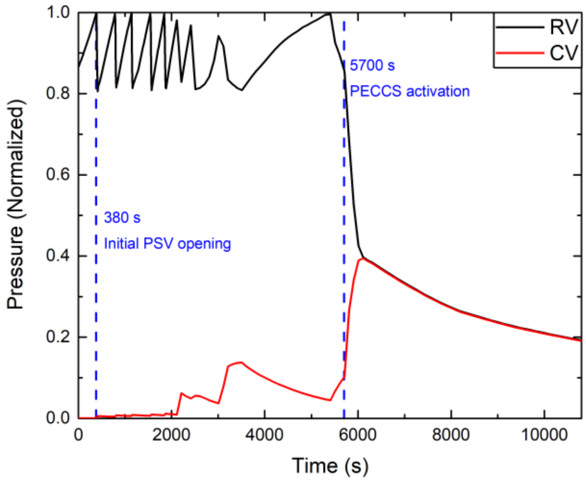

Fig. 1. Pressure of RV and CV (3 hours)

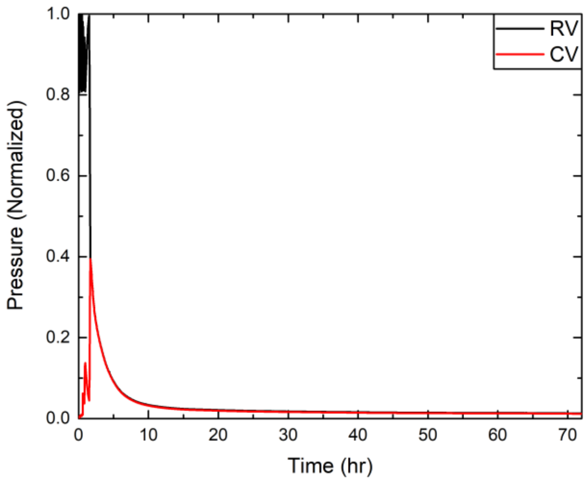

Fig. 2. Pressure of RV and CV (72 hours)

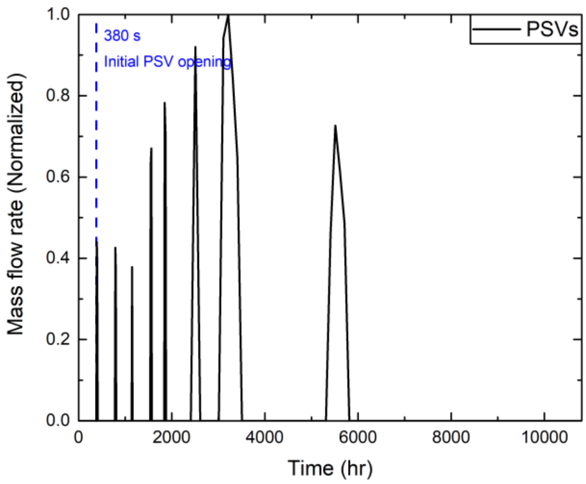

Fig. 3. Mass flow rate of PSVs (3 hours)

As shown in **Fig. 4, 5**, when the reactor system reached the PECCS actuation condition at about 5,700 seconds, both the ERVs and the EDVs were opened.

The mass flow rate through these valves is represented such that flow from the RV to the CV appears as a positive value for the EDV, and flow from the CV to the RV appears as a positive value for the ERV. Upon the valve opening, the RV released a significant amount of coolant to the CV, rapidly equalizing the pressure between the two volumes. The discharged vapor subsequently was condensed by heat removal from the PCCS heat exchanger, leading to an increase in the water level inside the CV.

Fig. 6 shows the water level in both the RV and CV. Initially, upon valve opening, both the EDVs and ERVs directed coolant from the RV to the CV. The EDVs continued discharging coolants from the RV to the CV. In contrast, after the CV water level exceeded the RV water level, the flow through the ERVs reversed at about 8,610 seconds. This reversal established a recirculation loop, with condensed coolant from the CV flowing back into the RV through the ERVs. As result, the recirculation maintained the RV water level and prevented core uncover.

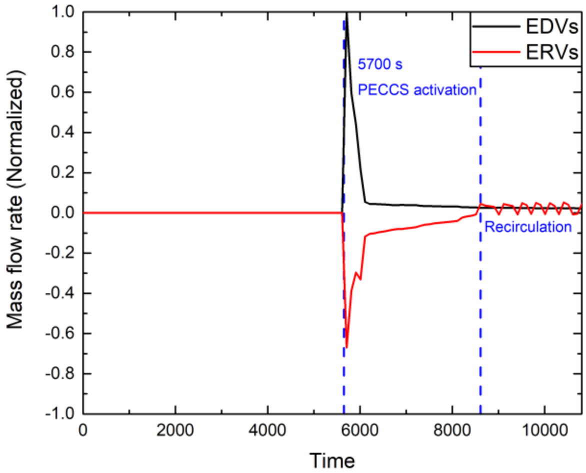

Fig. 4. Mass flow rate of EDVs and ERVs (3 hours)

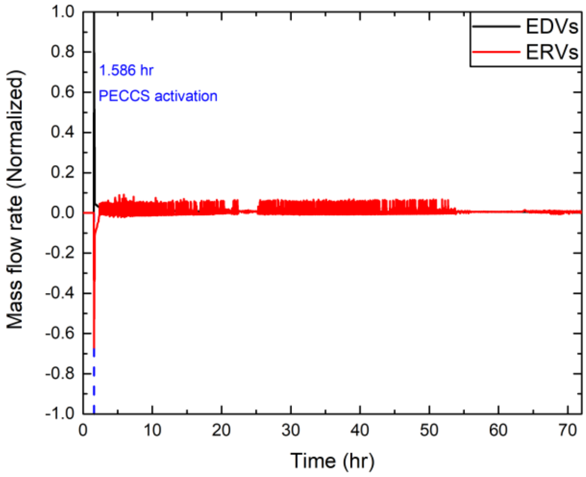

Fig. 5. Mass flow rate of EDVs and ERVs (72hours)

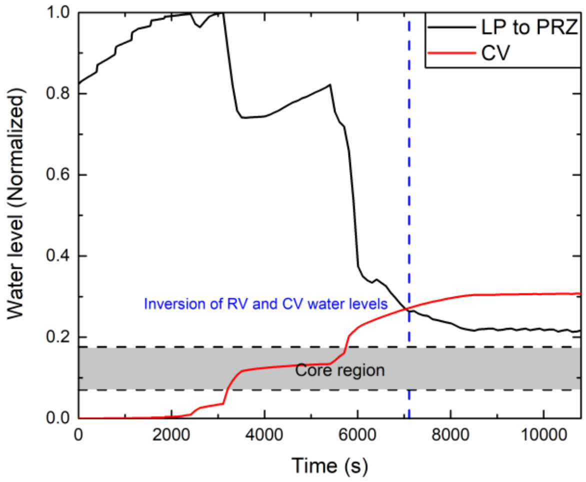

Fig. 6. Water level in RV and CV (3 hours)

Over the 72 hours of the accident, **Fig. 7** confirms that core uncover did not occur. Moreover, **Fig. 8** shows that the core exit, fuel, and cladding temperatures did not increase significantly during this period. These observations suggest that depressurization of the PSVs, steam condensation through the PCCS, and coolant recirculation through the PECCS effectively maintained RV pressure and coolant inventory. Consequently, adequate core cooling was secured, thereby preventing cladding oxidation and core degradation.

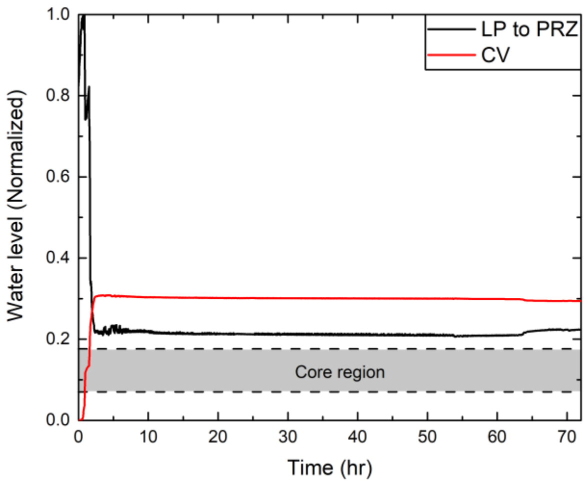

Fig. 7. Water level in RV and CV (72 hours)

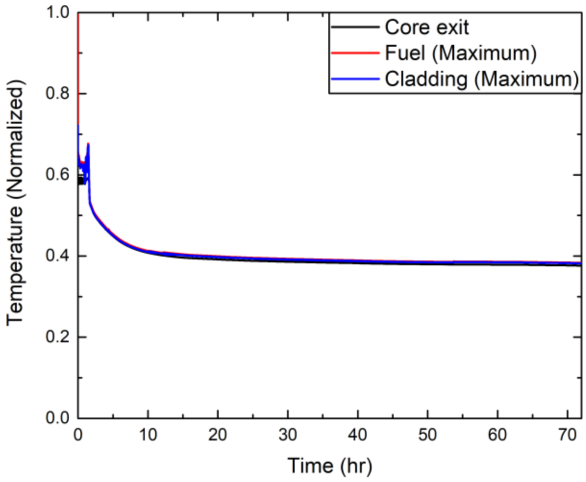

Fig. 8. Temperature of core exit, fuel and cladding (72 hours)

4. Conclusions

This preliminary investigation of the i-SMR accident scenario using CINEMA shows that the passive safety systems can effectively mitigate accident progression under the SBO scenario. The major findings are as follows:

1) The PSVs operation controlled the RV pressure by releasing hot steam into the CV, preventing excessive pressure increase.

2) Activation of the PECCS formed recirculation through the EDVs and the ERVs. The coolant condensed by the PCCS was reinjected into the RV through the ERV to maintain the coolant inventory in the RV.

3) For 72 hours after the accident, core exit, fuel, and cladding temperature were maintained within safe limits to prevent core uncover and accident acceleration.

These results demonstrate the potential of i-SMR's passive safety system to ensure core cooling and structural integrity in SBO accident scenario.

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