Preliminary source term analysis of INCV-LOCA in i-SMR using CINEMA code

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1. Introduction

The i-SMR (Innovative Small Modular Reactor) is a cutting-edge 170MWe integrated pressurized water reactor that delivers superior reliability, cost-effectiveness, and adaptability compared to other small modular reactors in operation worldwide. Utilizing passive safety mechanisms driven by natural circulation, it achieves intrinsic safety through a more compact and simplified configuration. In every type of accident scenario, even under extreme conditions, the plant can automatically shut down and ensure continuous, long-term heat removal indefinitely without requiring human intervention, external electricity, or supplemental coolant injection [1].

Two distinct types of safety valves are employed to establish a direct connection between the RV (Reactor Vessel) and the CV (Containment Vessel), the latter of which provides an external barrier surrounding the RV. Specifically, the EDV (Emergency Depressurization Valve) is installed at the uppermost region of the pressurizer, whereas the ERV (Emergency Recirculation Valve) is situated at the bottom of the SG (Steam Generator). Both valves are engineered to be actuated automatically upon receipt of a designated signal, thereby eliminating the necessity for operator involvement during their operation. Following a reactor trip, the primary coolant is able to circulate between the RV and the CV, which facilitates the continuous removal of residual heat through the combined action of the PCCS (Passive Containment Cooling System) and PAFS (Passive Auxiliary Feedwater System). PAFS supplies auxiliary feedwater to the SG through natural circulation, enabling long-term removal of decay heat without external power or operator action. PCCS maintains CV integrity during accident conditions by condensing steam and transferring heat, thereby suppressing pressure and temperature rise without external power. The passive safety concept of the i-SMR is shown in Fig. 1.

As a distinctive design characteristic of the i-SMR, large-diameter piping for the NSSS (Nuclear Steam Supply System), such as the cold and hot legs commonly found in conventional nuclear power plants with large containments, has been eliminated. Nevertheless, several penetration lines remain for normal operation, including the feedwater, steam line, and MMPS (Modular Makeup and Purification System). LOCA (Loss of Coolant Accident) may occur in the event of an MMPS line rupture, and when such an accident takes place inside the CV, it is referred to as an INCV-LOCA [3]. In i-SMR, two MMPS connections are provided: the L/D (Letdown) line is positioned at the upper section of the SG, while the C/G (Charging) line is placed at the lower part of the SG. The penetration piping arrangement of the i-SMR is depicted in Fig. 2.

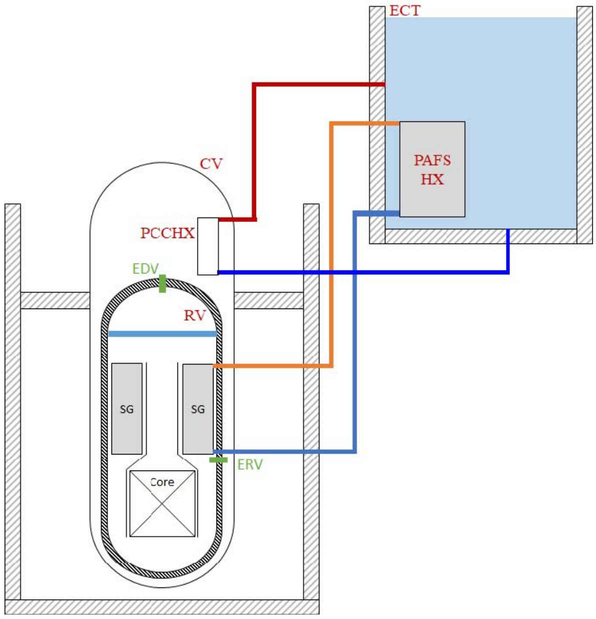

Fig. 1. Safety features of i-SMR [2]

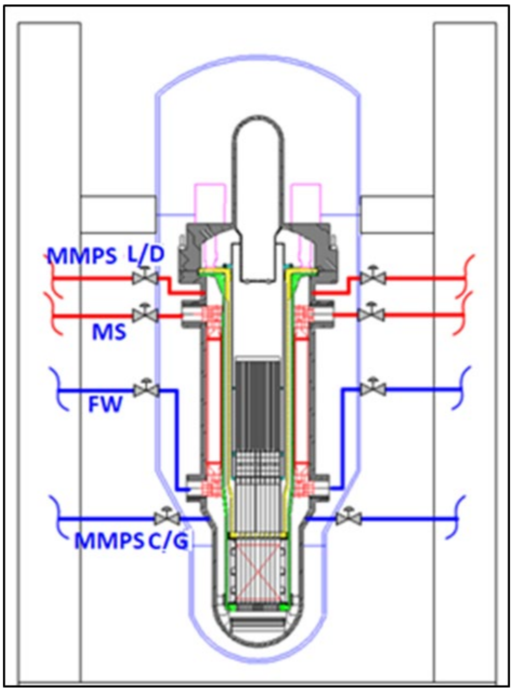

Fig. 2. Penetration pipe lines of i-SMR [2]

The CINEMA code is an integrated computational framework designed to perform coupled analyses by linking multiple specialized modules, each of which can independently simulate distinct phenomena occurring during a severe accident. To systematically address the complex processes involved, CINEMA classifies severe accident phenomena into in-core and ex-core categories. As depicted in Fig. 3, the code consists of three primary analysis modules, with their specific areas of application defined as follows [4]: CSPACE, which addresses system thermal hydraulics and in-core phenomena; SACAP, which focuses on system thermal hydraulics and ex-core phenomena; and SIRIUS, which models the behavior of FPs (Fission Products) throughout the accident progression.

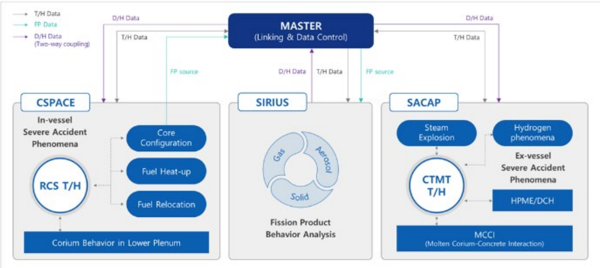

Fig. 3. Structure of CINEMA code [4]

In this research, preliminary source term analysis of INCV-LOCA in i-SMR using CINEMA code will be performed. The release fraction to the environment was calculated by assuming that FPs are discharged through the CV leak at a flow rate of 0.1 vol% per day.

2. Effect of Break Location on INCV-LOCA

In this section, two INCV-LOCA scenarios were analyzed to investigate the effect of break location on the source term results:

- Case 1: INCV-LOCA (MMPS C/G line break) * EDV failure (0/2) * ERV failure (0/2) * PCCS success (4/4)
- Case 2: INCV-LOCA (MMPS L/D line break) * EDV success (2/2) * ERV failure (0/2) * PCCS success (4/4)

A break occurs in the MMPS C/G line for Case 1, which corresponds to the lower line of the MMPS, with both EDV and ERV failure, and a break occurs in the MMPS L/D line for Case 2, which corresponds to the upper line of the MMPS, with EDV operating successfully and ERV failure. Complete failure of PAFS and fully success operation of PCCS were assumed for Case 1 and 2. Table I shows the main events of INCV-LOCA with different break locations in i-SMR. The accident is assumed to occur at time zero, and 3,000s steady-state simulation was conducted to ensure that key design parameters are satisfied within 1% margin of error.

Table I. Main events of INCV-LOCA in i-SMR

Event	Time (C/G line)	Time (L/D line)
INCV-LOCA occurrence	0 s	0 s
Rx, RCP, MFWP trip	2 s	3 s
Core top uncovering	130 s	150 s
EDV open (ERV fail to open)	-	2,070 s
SAMG entry (Core exit temp. > 923 K)	2,654 s	14,598 s
Gap release (Cladding temp. > 1173 K)	2,589 s	14,674 s
Cladding oxidation	2,589 s	14,677 s
Corium relocation to core support plate	3936 s	17,490 s
Corium relocation to lower plenum	6,586 s	20,094 s
RV failure	-	-
End of simulation	259,200 s	259,200 s

In Case 1, although the pressure difference between the pressurizer and the CV decreases and the downcomer water level is reduced following the accident, the EDV remains closed, resulting in a smaller effective flow area connecting the RV and the CV compared to Case 2, where the EDV is actuated after the accident. This difference leads to a more rapid progression of the accident in Case 1. Fig. 4 demonstrates that the CV pressure is sustained at a higher level in Case 1. This is because, as shown in Fig. 5, the water level in Case 1, similar to Case 2, is maintained above the MMPS C/G line break location; consequently, in Case 1, where the EDV does not open, the hydrostatic head of the CV contributes to the pressure equilibrium between the RV and the CV. As shown in Fig. 6, in Case 1, the water level does not remain at zero nor increase, because the amount of water supplied to the lower plenum through the break is insufficient due to counter-current flow and is immediately evaporated.

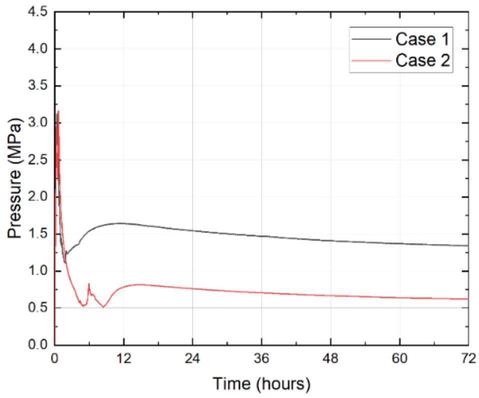

Fig. 4. CV pressure (Case 1 and 2)

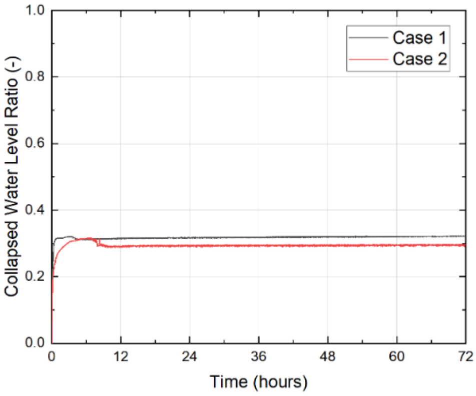

Fig. 5. CV collapsed water level ratio (Case 1 and 2)

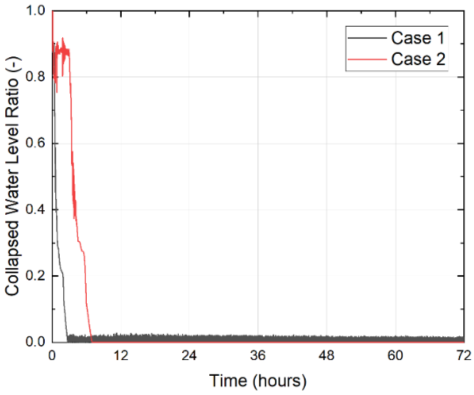

Fig. 6. Lower plenum and active core collapsed water level ratio (Case 1 and 2)

The results of the Cs (Cesium) release fraction to the environment are presented in Fig. 7, showing that the values in Case 1 are lower than those in Case 2. In Case 1, the core is directly cooled by water, which leads a relatively lower core temperature and consequently slow down FPs release. Also, the water-filled downcomer promotes upward transport of FPs from the core, enabling circulation within the RV before discharge through the break to the CV, thereby enhancing deposition within the RV such as primary side of SG, as illustrated in Fig. 8.

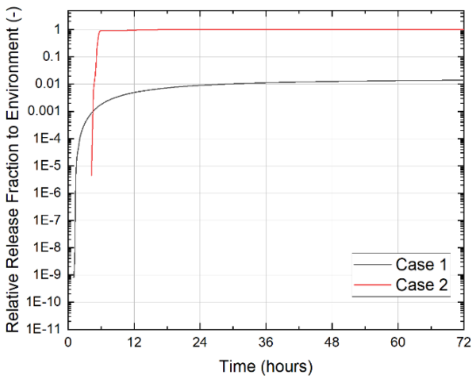

Fig. 7. Cs relative release fraction to environment (Case 1 and 2)

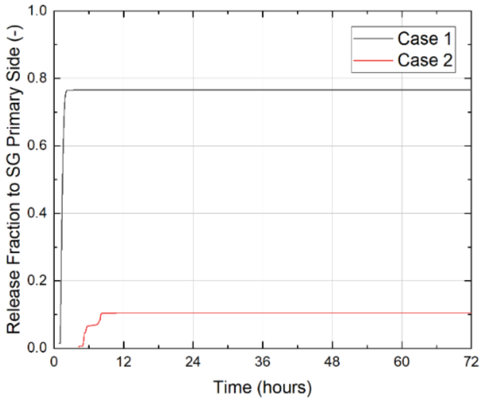

Fig. 8. Cs release fraction to SG primary side (Case 1 and 2)

3. Effect of PCCS Heat Removal Performance

In this section, the effect of PCCS heat removal performance on the source term was analyzed. In Case 3, the heat removal performance of the PCCS was assumed to be 50% of that in Case 2. As shown in Fig. 9, the CV pressure in Case 3 is higher than in Case 2 throughout the progression of the accident. The Cs release fraction to environment is determined by the pressure difference between the CV and the environment, and consequently, it is higher in Case 3 as shown in Fig. 10.

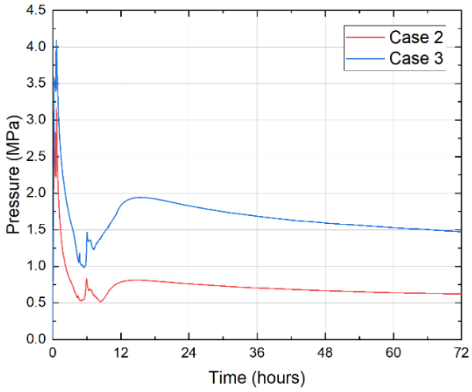

Fig. 9. CV pressure (Case 2 and 3)

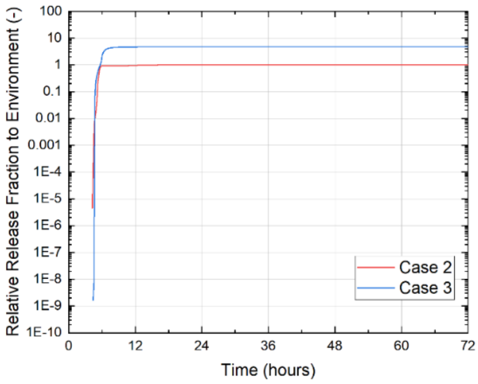

Fig. 10. Cs relative release fraction to environment (Case 2 and 3)

4. Conclusion

In this research, it was investigated the effect of break location and PCCS heat removal performance on the source term in the i-SMR under INCV-LOCA scenarios. In section 2, two break locations were considered for source term analysis: the lower MMPS C/G line (Case 1) and the upper MMPS L/D line (Case 2), with differing EDV and ERV operations. Compared to Case 2, Case 1 had a closed EDV and limited water supply to the lower plenum due to counter-current flow, resulting in higher CV pressure, and more FP deposition within the RV. The effect of reduced PCCS heat removal on the source term was examined in section 3, assuming a 50% decrease for Case 3 relative to Case 2. The results demonstrated that reduced PCCS heat removal performance elevates CV pressure and consequently increases the source term. As further research, a sensitivity analysis can be performed on the aerosol generation and removal models in SIRIUS.

Acknowledgement

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