Code-to-Code Comparison of Severe Accident Analysis for a Postulated i-SMR LOCA scenario Using CINEMA and MELCOR

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1. Introduction

With the advancement of artificial intelligence technologies, the energy demand of data centers and high-performance computing servers has significantly increased [1]. To address this growing demand, Small modular reactors (SMR) have attracted considerable attention as a sustainable and reliable power source capable of providing stable electricity under diverse operating conditions[2,3].

In Korea, extensive investigation for SDA for innovative small modular reactor (i-SMR) has been actively conducted across various technical field [4,5]. Among these essential studies, severe accident analysis constitutes a critical aspect, as it directly relates to the evaluation of plant safety margins under beyond-design-basis conditions and plays a key role in regulatory safety evaluations.

To analyze severe accident progression and identify key phenomenological characteristics, the use of system-level severe accident analysis codes is essential. In this study, severe accident simulation code, CINEMA [6] is employed to model the progression of the severe accident scenario for i-SMR. To assess the credibility and reliability of the simulation results, comparative analysis is performed against MELCOR [7,8], a widely used severe accident analysis code. Through this comparison, the applicability of CINEMA for i-SMR severe accident analysis is systematically evaluated [9].

2. Methodology

2.1 Scenario Description

In this study, a loss of coolant accident (LOCA) is postulated as a severe accident scenario for the i-SMR. The accident is initiated by a pipe rupture in the modular makeup purification system (MMPS) letdown line, with a break size of 2-inch diameter. The rupture leads to a continuous coolant leakage from the primary system.

To increase the severity of the accident, key passive safety features are assumed to be unavailable or partially available.

Passive auxiliary feedwater system (PAFS) is assumed to be unavailable in this scenario hence the secondary-side heat removal is not credited.

Regarding the passive emergency core cooling system (PECCS), a conservative availability assumption is applied. All emergency depression valves (EDVs) are assumed to be available (2/2), enabling primary system to depressurize when the signal is provided. In contrast, all emergency recirculation valves (ERVs) are assumed to be unavailable (0/2), preventing the recirculation of the condensed coolant located in the bottom of the containment vessel to the core.

The postulated accident scenario demonstrates highest frequency in LOCA accident in NuScale power US460 cutset evaluation in multi-module full-power situation [10].

A schematic of i-SMR, including the relevant pipelines and postulated break location, is presented in **Fig. 1**.

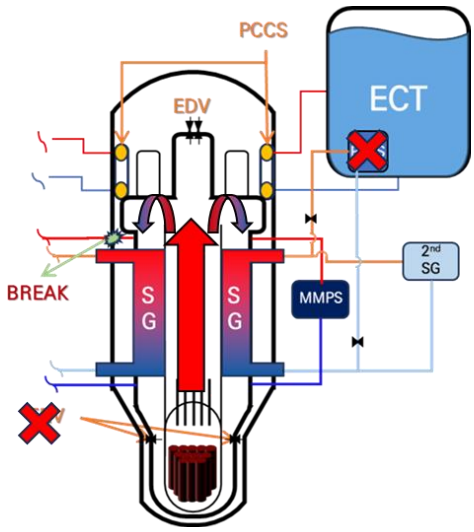

Fig 1. Diagram of i-SMR pipelines and assumptions made for depicting LOCA scenario

2.2 SA Analysis code: CINEMA

Korea is developing its own severe accident analysis code, CINEMA (Code INtegrated severe accident Evaluation and MAnagement). CINEMA consists of four packages with different purposes which are, CSPACE, SIRIUS, SACAP, and MASTER [9]. CSPACE interprets response of thermal-hydraulic behavior, SIRIUS investigates fission product behavior, and SACAP analyzes the phenomena occurred within containment building. Due to the absence of containment building in i-SMR, SACAP is not utilized in this study. The MASTER package controls the interaction between three packages and adjust the interpretation sequence.

2.3 SA Analysis code: MELCOR

MELCOR is a system code for Nuclear Regulatory Commission (NRC) to simulate the progression of SA and analyze accident phenomena. Adopted by the NRC since the early 1980s, MELCOR has been widely employed by numerous scholars to analyze the causes and effects within SA scenarios. Over its long history in the nuclear engineering field, the code has earned reliability and a reputation.

3. Result

3.1 Accident sequence difference

The progression simulation results are demonstrated in Table 1. A significant difference is observed in the coolant level decrement which occurs earlier and faster in MELCOR simulation. Such difference accelerates the progression of severe accident phenomena throughout the scenario.

Table I: Accident progression of LOCA analysis

Event	Timing(s)	
	CINEMA	MELCOR
INCV upper LOCA	0	0
Rx, RCP, MFWP trip	12.27	3.4
Core uncover start timing	8,150.01	5,450.0
SAMG entry timing (CET > 923.15K)	14,070.6	6,950.0
Cladding Oxidation	14,242.5	7,250.0
Gap Release	14,240.4	7,398.8
Core dry out	16,823.5	17,100.0
CSP failure	20,067.6	24,868.2

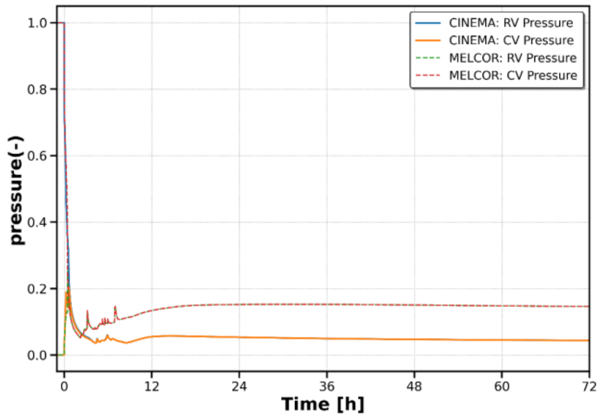

Fig 2. Pressure behavior of RV and CV comparison (72 hr)

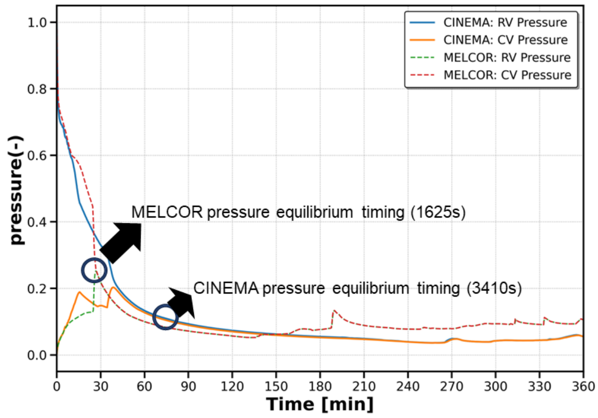

Fig 3. Pressure behavior of RV and CV comparison (6 hr)

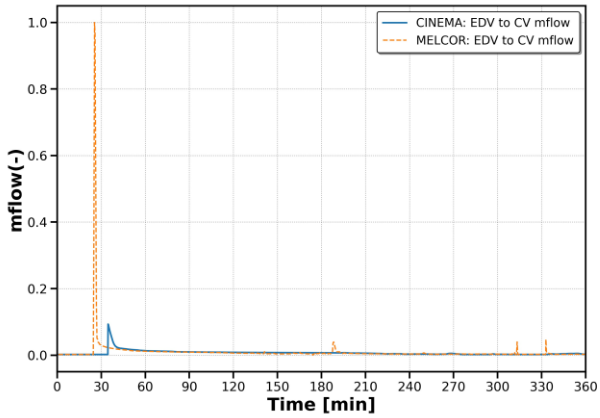

Fig 4. Mass flow rate through EDV comparison (6 hr)

As illustrated in Fig. 2 and, the MELCOR simulation demonstrates more rapid equilibrium between the RV and CV pressures. This leads to a corresponding decrease in the coolant's saturation temperature at earlier stage. The reason why the MELCOR demonstrates earlier progression is demonstrated in Fig. 4.

As illustrated in Fig. 4, the MELCOR simulation predicts a higher mass flow rate through the EDV compared to CINEMA. This increased rate of coolant discharge from the RV to the CV results in a more rapid pressure equilibrium, as demonstrated in Fig. 3. Consequently, the rapid pressure drop would decrease the coolant's saturation temperature at an earlier stage.

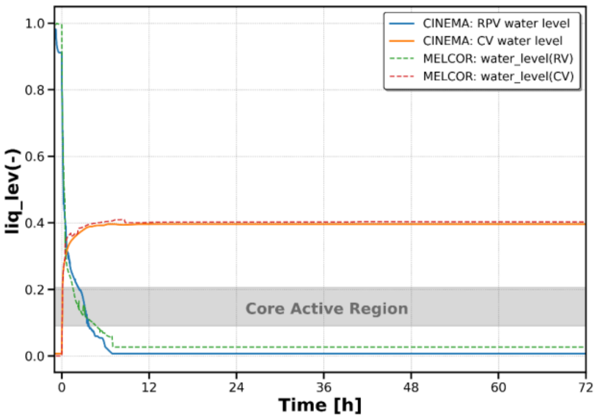

Fig 5. Water level behavior comparison (72 hr)

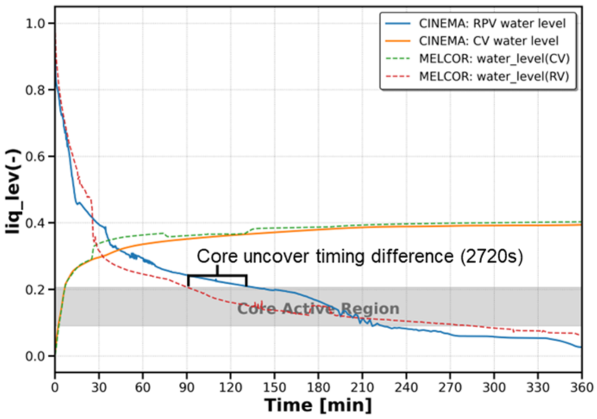

Fig 6. Water level behavior comparison (6 hr)

The decrease in saturation temperature leads to massive amount of boiling. Fig. 5 demonstrates overall water level behavior in reactor vessel (RV) and containment vessel (CV). Fig 6 emphasizes the difference in core uncover timing which is calculated as 2,720s between CINEMA and MELCOR.

Consequently, the coolant inventory decreases in higher speed, accelerating the overall progression of the severe accident. Two of the main phenomena in severe accidents, core exit temperature and hydrogen mass are depicted in Fig. 6 and 7.

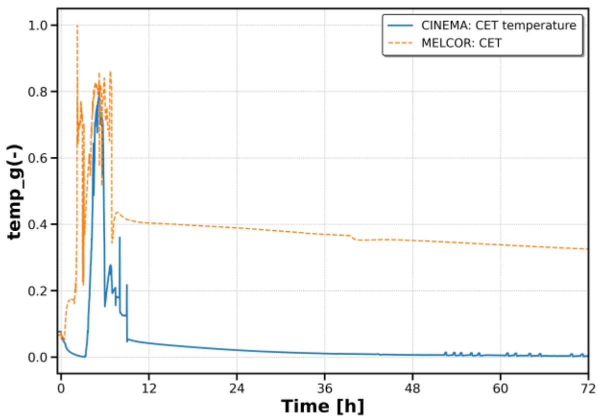

Fig 7. Core exit temperature behavior comparison (72 hr)

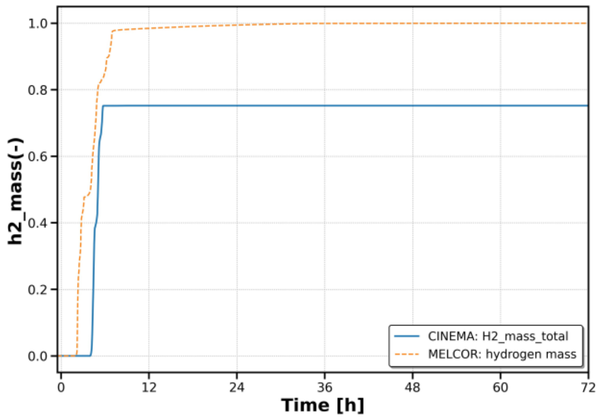

Fig 8. Hydrogen mass behavior comparison (72 hr)

4. Conclusions

In In this study, a code-to-code comparative analysis was performed for a postulated loss of coolant accident (LOCA) scenario in an innovative small modular reactor (i-SMR) using the CINEMA and MELCOR system codes. Based on the analysis results, the following major conclusions were drawn.

A clear difference was observed in the predicted accident progression speed between the two codes. MELCOR predicted the onset of core uncovering approximately 2,720 seconds earlier than CINEMA. This difference is primarily attributed to MELCOR's higher calculated coolant discharge rate through the emergency depressurization valves (EDVs), which leads to an earlier pressure equalization between the reactor vessel (RV) and the containment vessel (CV).

In addition, differences in safety margin assessment were identified. Based on the severe accident management guideline (SAMG) entry criterion (core exit temperature, CET > 923.15 K), MELCOR predicted SAMG entry at approximately 6,950 seconds, whereas CINEMA predicted entry at 14,070 seconds. This result indicates that MELCOR provides a more conservative prediction, nearly two times earlier than CINEMA. The root cause for such difference in the calculation is expected to be from either input models of the system and need to be further investigated.

Future studies will focus on detailed fission product behavior analysis and refined assessments incorporating updated i-SMR design parameters. The results of this study are expected to serve as foundational technical evidence supporting regulatory applications for i-SMRs and the analytical validity of the CINEMA code.

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