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Comparative Analysis on the Fission Product Behavior under the SBLOCA Scenario in OPR1000 Using CINEMA and MELCOR Codes

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1. Introduction

As severe accidents such as TMI-2, Chernobyl, and Fukushima showed catastrophic consequences, effective tools for predicting and managing severe accidents in nuclear power plants have been actively developed such as MAAP, ASTEC, and MELCOR. In particular, MELCOR is widely used by many countries for regulating the design and safety of nuclear power plants and can be utilized to analyze the complex thermal hydraulic phenomena under severe accident conditions.

Recently, in South Korea, CINEMA (Code for INtegrated severe accident Evaluation and Management) has been under development to establish a domestically independent severe accident analysis system [1]. However, CINEMA still has room for further improvement. Thus, it is essential to validate CINEMA by comparing its performance with other well-established severe accident analysis codes like MELCOR.

A comparative analysis with CINEMA using MAAP and MELCOR have been conducted previously, focusing on the overall accident progression rather than specific and detailed phenomena [2], [3]. However, severe accident management strategies primarily target the analysis of specific phenomena such as the behavior of fission products [4]. To maintain the integrity of the containment building and prevent the release of radioactive materials, the behavior of fission products needs to be evaluated. Additionally, the assessment of fission product behavior has crucial aspect of environmental safety features, as the transport and release of fission products significantly impact radiological risk.

Therefore, in this study, the fission product behavior during a severe accident in OPR1000 was analyzed using SIRIUS (SImulation of Radioactive nuclide Interaction Under Severe accident) 2.0.2.356 module in CINEMA 2.0.2 and RN (RadioNuclide) package in MELCOR 2.2. Thereafter, the behavior of fission products evaluated by the respective methodology was compared with each other.

2. Methodology

The SIRIUS module in CINEMA classifies radionuclides into 8 representative groups based on similar chemical properties, while the RN package in MELCOR divides radionuclides into 16 classes based on their chemical characteristics. Although various radionuclides are released during severe accidents, this study focuses on Xe, Cs, and CsI, which are considered the main fission products released in the largest quantities [5]. In CINEMA, I (Iodine) immediately combines with Cs (Cesium) to form CsI (Cesium Iodide) upon release, with the remaining Cs forming CsOH (Cesium HydrOxide). Unlike this, MELCOR simulates the behavior of Cs, I_2, and CsI separately.

When fission products are released, they move as gases and aerosols, either floating the atmosphere or depositing on the RCS (Reactor Coolant System) and the containment building. To evaluate the integrity of containment building, this study compared the amount of fission products released into the containment with the initial loading. Additionally, it assessed the amount of airborne material, including both gas and aerosol forms, within the containment relative to the initial loading of fission products.

Figure 1 shows the OPR1000 nodalization for CINEMA used in this study, which was mainly developed by KAERI (Korea Atomic Energy Research Institute). Figure 2 presents the OPR1000 nodalization for MELCOR 2.2 used in this study. Both input models include the NSSS (Nuclear Steam Supply System), BOP (Balance Of Plant), and the containment building. The figures particularly illustrate the detailed NSSS components such as core region, hot legs, cold legs, and pressurizer.

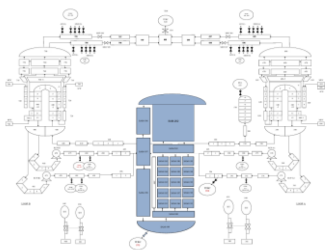

Fig. 1. CINEMA input model of OPR1000

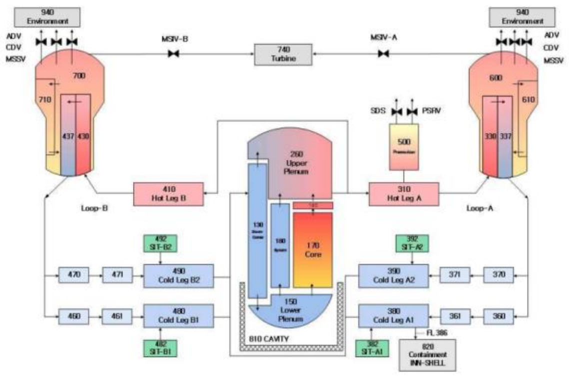

Fig. 2. MELCOR input model of OPR1000

The accident scenario considered in this study is the SBLOCA (Small Break Loss of Coolant Accident), which has the highest probability of progressing into a severe accident in the OPR1000 reactor [6]. The break occurs in the cold leg of the loop with the pressurizer, with a break size of 1.35 inches. In this scenario, no operator actions or mitigation strategies were implemented to mitigate the accident after its occurrence. Additionally, the scenario assumes that a reactor trip and RCP (Reactor Coolant Pump) trip occur immediately upon the start of the accident due to the break. Table I outlines the key events and times simulated by CINEMA and MELCOR during this accident scenario.

Table I. The key events of the SBLOCA scenario

Accident Sequence	Time (s)	
	CINEMA	MELCOR
Accident Start	0	0
Reactor trip	0	0
RCP trip	0	0
SG dry-out	3030	5730
Oxidation start	5000	7680
SAMG entrance	4990	7731
Core dry-out	5060	9060
Cladding melt	6320	8689
UO2 melt	6510	9115
Relocation	7340	10178
SIT injection	6630, 9660~	12205, 13991~
RPV failure	11410	13891

3. Results and Discussion

Figures 3 (a) and (b) show the release fraction of Xe into the containment building and the suspended fraction within atmosphere of the containment building, as calculated by CINEMA and MELCOR, respectively. According to both results, over 99% of the initial Xe inventory was released into the containment building. As an inert gas, Xe was entirely in the gas phase and was fully suspended in the containment building.

Figures 3 (c) and (d) present the release and airborne fractions of Cs into the containment building. In MELCOR, approximately 62% of the Cs inventory was released into the containment building, where most of it deposited into pools due to the cooling effects of the containment building outer walls. However, in CINEMA, a significant amount of Cs was deposited within the RCS, with only about 23% being released into the containment building.

The behavior of CsI followed a similar trend to that of Cs. Figures 3 (e) and (f) show the release and airborne fractions of CsI into the containment building. In MELCOR, about 96% of the CsI inventory was released into the containment building, with over 80% of the released amount depositing into pools. Conversely, in CINEMA, only about 22.5% of CsI was released into the containment building, with the majority being deposited within the RCS. Table II summarizes the release and airborne fractions of Xe, Cs, and CsI as calculated by CINEMA and MELCOR.

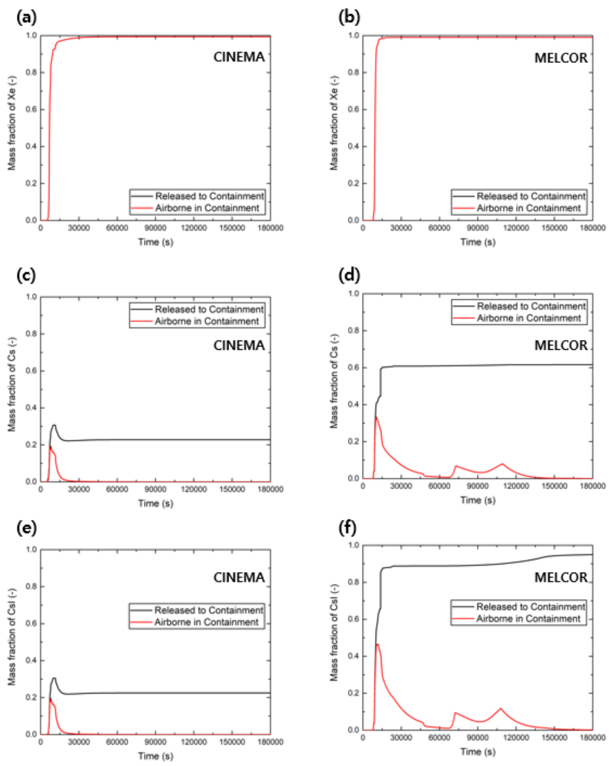

Fig. 3. (a) Behavior of Xe (CINEMA), (b) Behavior of Xe (MELCOR), (c) Behavior of Cs (CINEMA), (d) Behavior of Cs (MELCOR), (e) Behavior of CsI (CINEMA), (f) Behavior of CsI (MELCOR)

Table II. Release and airborne fraction of Xe, Cs, CSI in containment building

Type of fission products		Mass fraction (%)	
		CINEMA	MELCOR
Xe	Released to containment	99.40	99.07
	Airborne in containment	99.40	99.07
Cs	Released to containment	22.78	61.62
	Airborne in containment	0.00	0.01
CsI	Released to containment	22.48	95.69
	Airborne in containment	0.00	0.31

In CINEMA, the release fractions into the containment building of Cs and CsI were significantly lower, approximately 22%. Over 50% of Cs and CsI released from the core were deposited on the hot leg and steam generator walls of the loop where the break occurred. This result seems to be attributed to the fact that, during the generation of fission products, most of the RCS flow from the core was directed towards the broken loop. As a result, the fission products were primarily transported into that loop. During this period, the fluid temperature in the hot leg and steam generator of the broken loop was lower than the saturation temperature. Consequently, a large portion of aerosols may have collided as they were transported, leading to their sedimentation under gravity. Additionally, the aerosols could have collided with the walls in the curved pipes while moving from the hot leg to the steam generator, resulting in further deposition. The relatively cooler walls of the surrounding structures likely contributed to condensation, causing a significant amount of deposition in those areas. Furthermore, Figure 4 shows that in CINEMA, the amount of CsI deposited on the RCS kept increasing and did not get re-released into the containment building.

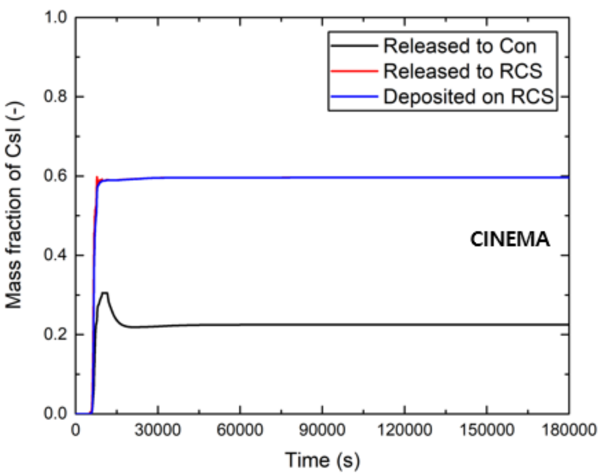

Fig. 4. Detailed behavior of CsI simulated by CINEMA

In contrast, MELCOR predicted significantly higher release fractions of Cs and CsI into the containment building, compared to CINEMA. Figure 5, which shows the detailed behavior of CsI simulated in MELCOR, illustrates that about 50% of CsI released from the core was initially deposited on the RCS walls or suspended in the pool or remained airborne. However, MELCOR models include the evaporation of fission products, which leads to the re-release of deposited fission products into the containment building and reduced the amount of CsI deposited on the RCS. Additionally, MELCOR includes the suspension of fission products in the pool, which caused their release into the containment building during RPV failure and further decreased the amount of CsI suspended in the RCS pool.

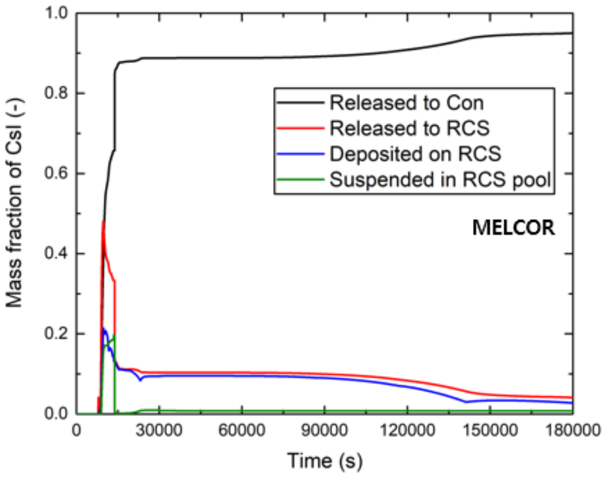

Fig. 5. Detailed behavior of CsI simulated by MELCOR

4. Conclusions

This study compared the behavior of fission products, specifically Xe, Cs, and CsI, during a severe accident in OPR1000 using CINEMA and MELCOR. The predictions for Xe behavior were consistent between the two codes. However, significant discrepancies were observed in the predictions for Cs and CsI behavior. The major findings are summarized as follows:

(1) Both codes showed that over 99% of Xe was released into the containment building and remained suspended.
(2) MELCOR predicted more than 60% of CsI and Cs were released into the containment building, with most depositing in pools, whereas CINEMA predicted about 22% were released, with the majority deposited within the RCS.
(3) The differences in CsI and Cs behavior between two codes were caused by the modeling of fission product evaporation and suspension in the pool. As a result, CINEMA predicted greater deposition within the RCS and lower release of fission products into the containment.

The results of this study highlight the importance for accurate modeling on the fission product transport and deposition during a severe accident. To predict the fission product behavior precisely, continued validation between severe accident analysis codes needs to be performed.

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REFERENCES

[1] Korea Hydro & Nuclear Power Co., Ltd., User Manual for CINEMA 2.0, 2022.
[2] Song C, et al., Benchmarking of PHEBUS FPT0 experiment by using CINEMA and MELCOR code, KNS Autumn Meeting, Changwon, Korea, October 20-21, 2022.
[3] Song, J., Son, D.-G. et al. (2023) A comparative simulation of severe accident progressions by CINEMA and MAAP5. Nucl. Eng. Des. 404 (2023), 112181.
[4] Severe Accident Management Programmes for Nuclear Power Plants, INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna, 2009.
[5] L.S. Lebel, R.S. Dickson, G.A. Glowa, Radioiodine in the atmosphere after the Fukushima Dai-ichi nuclear accident, J. Environ. Radioact. 151 (2016) 82–93.
[6] Yongjae Lee, Wonjun Choi, Joong Kim Sung (2017). Efficacy assessment of independent severe accident mitigation measures in OPR1000 using MELCOR code. J. Nucl. Sci. Technol., 54 (1), 89–100.