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Performance Evaluation of Conceptual Hybrid Safety Injection Tank under SBO Accident by Using MELCOR Code

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1. Introduction

Following the Fukushima Nuclear Power Plant (NPP) accident in 2011, numerous research activities have been actively conducted on the interpretation and mitigation measures of severe accidents to improve the safety of NPPs. Particularly analyses of representative Design Basis Accidents (DBAs) such as Small Break Loss of Coolant Accident (SBLOCA), Station Blackout (SBO), and Total Loss of Feed Water (TLOFW) have been considered and prioritized [1]. Among these accidents, SBO stands out due to its potentially significant risk because it involves a loss of alternating current (AC) power, limiting the availability of an active safety systems to mitigate the accident. Consequently, there is a growing emphasis on the development and installation of passive safety systems capable of mitigating accidents without electrical power source. Indeed, many small modular reactors under present development embody innovative passive safety systems, which can reduce the likelihood of severe accidents substantially [2].

Through the design and construction history of the light water reactor, passive safety systems play a crucial role in accident mitigation, with the Safety Injection Tank (SIT) being a representative passive safety system of large-scale reactors like Optimized Power Reactor 1000 MWe (OPR1000). The SIT is designed to inject emergency coolant into the primary system when primary pressure drops below 4.3 MPa [3]. However, during SBO accident, pressure in the primary system remains high until Reactor Pressure Vessel (RPV) failure because depressurization valve is inoperable, resulting in the SIT's function unavailable. Therefore, Hybrid Safety Injection Tank (HSIT) have been conceptualized to pressurize SIT before RPV failure, enabling emergency coolant injection even during high-pressure accidents. Existing studies about the HSIT have conducted experimental and analytical research on the performance and optimal operation strategies of the HSIT [4]. However, there has been no research evaluating the applicability of HSIT in mitigating SBO accident in OPR1000 using severe accident analysis codes. Therefore, this study evaluates the capability of mitigating accident of the HSIT under the SBO in OPR1000 using severe accident analysis code. For this evaluation, the MELCOR 1.8.6. code developed by the Sandia National Laboratories (SNL) was utilized. By using the MELCOR code, various severe accident phenomena such as core degradation, RPV failure, behavior of combustible gases and fission product can be simulated effectively [5].

2. Methodology

2.1 MELCOR Input Model of OPR1000

Figure 1 illustrates the nodalization of the MELCOR input, specifically Reactor Coolant System (RCS), of the OPR1000. The RCS consists of primary systems including the lower plenum, reactor core, upper plenum, two hot legs, four cold legs, pressurizer, and four SITs. Additionally, the input model includes secondary system with some valves of the main steam supply system and containment building.

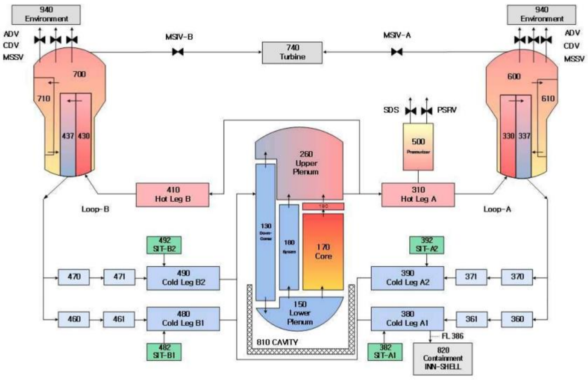

Fig.1. MELCOR nodalization of OPR1000

2.2 Hybrid Safety Injection Tank (HSIT) Model

HSIT was designed to function similarly to conventional SIT, which is pressurized with nitrogen gas to 4.3 MPa. Unlike the conventional SIT, in the event of a high-pressure accident the check valve connected to the pressurizer through a pressure balancing line in the HSIT opens. Upon opening the check valve, the high pressure from the pressurizer pressurizes the HSIT via the pressure balancing line, enabling emergency coolant injection into the primary system by gravitational force in the event of primary system pressure drop [6]. Therefore, the coolant can be injected into the primary system without the operation of depressurization valves.

In this study, a total of four HSITs were modeled in the MELCOR input. To simulate the pressure balancing line in MELCOR, a Flow path (FL) 501 was modeled, connecting the pressurizer Control Volume (CV 500) and the SIT Control Volume (CV 382). For other SITs (CV 392, 482, and 492), FLs 503, 505, and 507 were made to model the pressure balancing line connected to the pressurizer. The initial pressure of each control volume of SIT and pressurizer was set to 4.3 MPa and 15.5 MPa, respectively. Additionally, to prevent backflow of pressure from the HSIT towards the pressurizer, check valves were created using FL valve input and Control Functions (CFs) defining fraction open, allowing one-directional pressure transfer only from the pressurizer to the HSIT direction. Figure 2 shows the schematic configuration of the HSIT modeling in MELCOR input model.

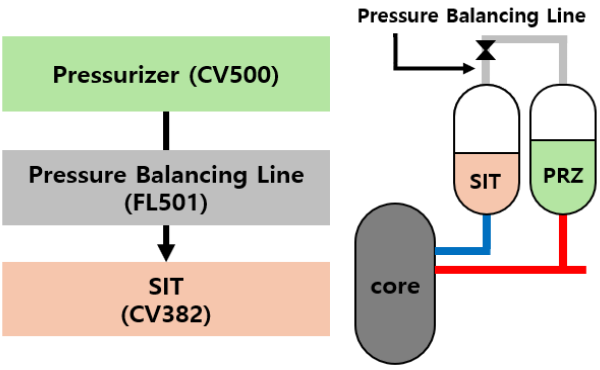

Fig.2. HSIT modeling in the MELCOR nodalization

2.3 Station Blackout (SBO) Scenario

The SBO scenario represents the initiating event of the severe accident in this study. This accident involves the complete loss of AC power within the OPR1000 due to events such as natural disasters or instability in the power grid. Therefore, safety systems that require power rely solely on Direct Current (DC) power supplied from on-site batteries, which have limited capacity [7].

The major sequence of accident progression of the SBO accident is summarized in Table I. Postulated accident scenario of this study is SBO accident with assumption that all operators take no response actions and safety system controlled by DC power fails to operate. To quantitatively assess the extent of accident delay by replacing SITs with HSITs, the SBO base case scenario, where HSITs are not installed and no mitigation started implemented, is analyzed first. Subsequently, the extent of SBO accident delay is evaluated by progressively increasing the number of HSIT installations to replace SITs.

Table I: The major event of the SBO accident

Accident Sequences	Time (hr)
Accident Start	0
Reactor Trip	0
PSRV open	1.36
SAMG entrance	2.25
Core dryout	2.62
Cladding melt	2.66
UO_2 melt	2.68
RPV failure	3.75
SIT injection	3.82
SIT exhaust	4.00

3. Results and Discussion

3.1 SBO Base Case Analysis

Figure 3 shows the primary system pressure over time in the SBO base case scenario without the HSITs. The SBO accident started at 0 s, and following the reactor trip, the primary system pressure increased due to the failure to remove heat from the core after the steam generator's water level on the secondary side was depleted. Simultaneously, the core temperature rose, reaching 923 K at 2.25 h, meeting the Severe Accident Management Guideline (SAMG) entrance condition [8]. Subsequently, with continued failure to remove heat from the core, the reactor experienced RPV failure after 3.75 h of reactor trip. As a result of the RPV failure, the pressure in the primary system rapidly decreased, and the operating pressure of the SIT reached 4.3 MPa, with emergency cooling water injected into the core at 3.82 h after RPV failure. Therefore, if emergency coolant from the SIT is injected into the primary system before RPV failure, it can be expected to ensure sufficient cooling performance delay the core degradation.

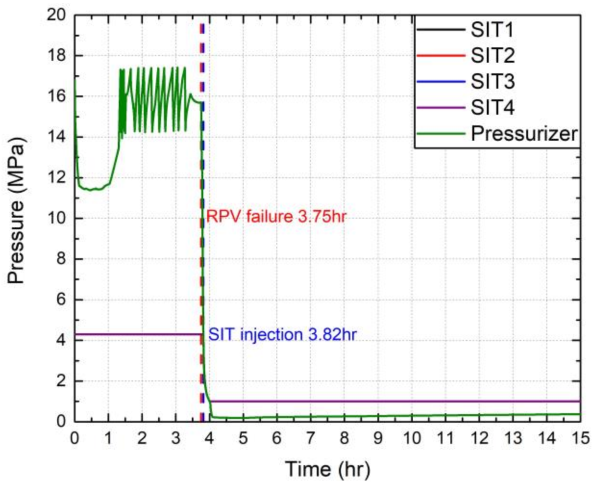

Fig.3. Pressure of primary system at SBO base case

3.2 HSIT Evaluation to Accident Mitigation

The effectiveness of HSIT in delaying accidents was assessed based on the delay in SAMG entrance, core dryout, relocation to lower plenum, and RPV failure times. Table II shows the times for each accident sequence corresponding to different numbers of HSITs. In Table II, “SIT injection” refers to the coolant injection from the conventional SITs, not HSITs. Therefore, when all four HSITs were in operation, there was no coolant injection from the conventional SITs, hence “N/A” is indicated in Table II.

Figure 4 shows the different tendency in water level of SITs and HSITs during the accident progression when two out of four SITs were operating as HSITs. The water level of SITs exhibited a pattern similar to the previous base case, with water level declining upon coolant injection into the primary system after RPV failure. However, unlike the SITs, the water level of HSITs decreased before the RPV failure, indicating that coolant from HSITs was injected into the primary system before RPV failure, thus suggesting a delay in each accident sequence.

Figure 5 shows the Core Exit Temperature (CET) according to the number of HSITs. For each case, the time when CET reaches 923 K, indicating SAMG entrance, was determined. Comparing with the base case, SAMG entrance was delayed by 1.28 h, 2.48 h, 3.57 h, and 4.71 h with each additional HSIT. The delayed SAMG entrance provides operators with additional time for emergency operation actions before severe accident.

Figure 6 shows the core water level and core dryout times according to the number of HSITs. In the base case without HSITs, core dryout occurred at 2.62 h. As the number of HSITs increased, the timing of core dryout was also delayed, with a delay to 4.83 h when all SITs operated as HSITs. Accordingly, the time for relocation to the lower plenum was also delayed, increasing with the number of HSITs installed.

Figure 7 shows primary system pressure and delay in RPV failure time according to the number of HSITs. With one HSIT installed, RPV failure was delayed by 1.98 h compared to the base case, and RPV failure time gradually increased with the increasing number of HSITs. Ultimately, with four HSITs in operation, RPV failure was delayed by 5.92 h compared to the base case. Thus, delaying the release of molten core into the containment building provides additional time for in-vessel accident mitigation. Additionally, as RPV failure time was delayed with an increasing number of HSITs, the injection time of emergency coolant from the conventional SITs was also delayed. When four HSITs were operational, the delay in accident progression was most significant, with all emergency coolant within HSITs injected into the primary system before RPV failure. Therefore, it was evaluated that operating all four SITs as HSITs can effectively delay the SBO base case accident.

Table II: Accident sequence time with HSIT number

Accident Sequences	Time (hr)				
	Base case	HSIT 1	HSIT 2	HSIT 3	HSIT 4
SAMG entrance	2.25	3.53	4.73	5.82	6.96
Core dryout	2.62	3.9	5.15	6.31	7.45
Relocation	2.83	3.99	5.22	6.38	7.55
RPV failure	3.75	5.73	7.02	8.39	9.67
SIT injection	3.82	5.77	7.1	8.46	N/A

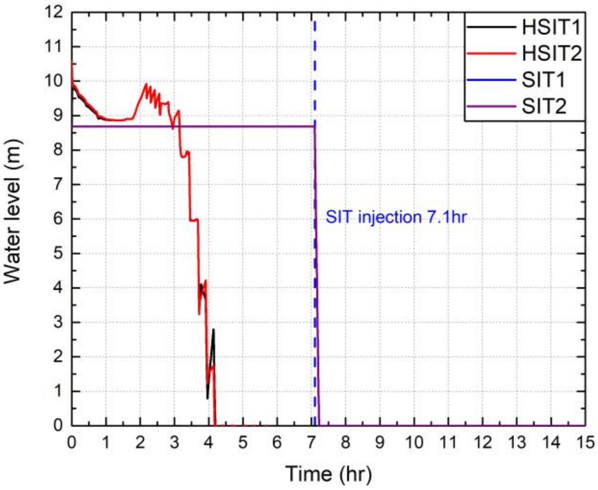

Fig.4. Water level of HSIT and SIT at case, which mitigated as two HSITs and two SITs

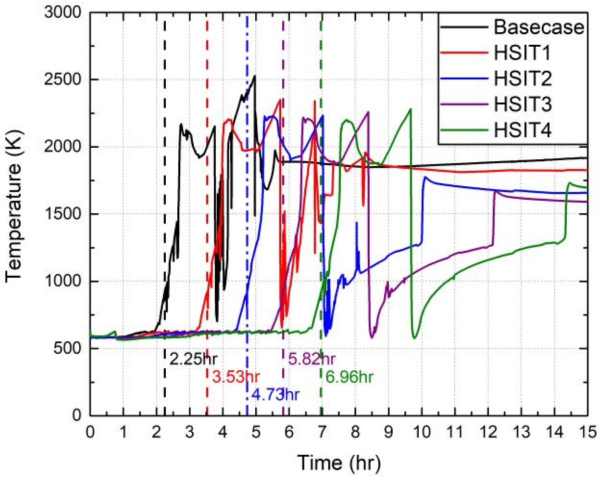

Fig.5. Core exit temperature and SAMG entrance time with HSIT number

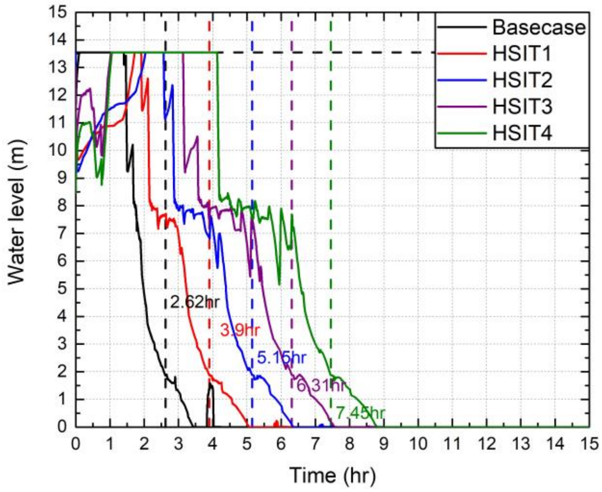

Fig.6. Core water level and core dryout time with HSIT number

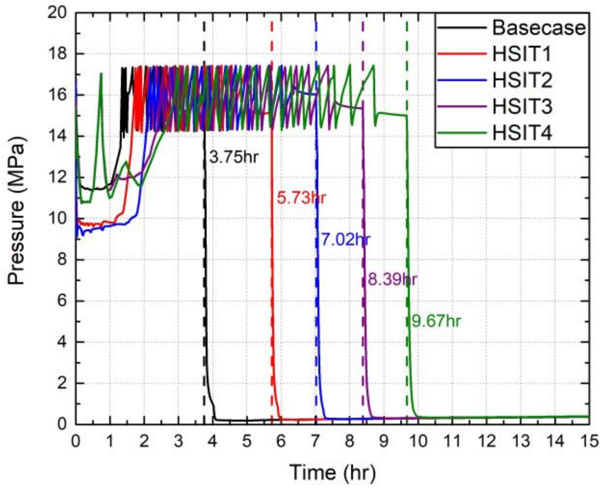

Fig.7. Pressure of primary system and RPV failure time with HSIT number

4. Conclusions

Using MELCOR 1.8.6. code, the performance of HSIT was evaluated by analyzing the extent of accident delay according to the number of HSIT under SBO accident in OPR1000. The times of SAMG entrance, core dryout, and RPV failure of each HSIT installation scenario were compared with the SBO base case. The main conclusions of this study can be summarized as follows.

(1) SBO accident is effectively delayed by HSITs, which inject emergency coolant into the primary system during the early stage of accident, thereby delaying core dryout.
(2) With an increase in the number of HSITs, SAMG entrance and RPV failure times are further delayed providing operators with additional time for emergency actions and enhancing accident response capabilities.
(3) In this study, the timing of check valve opening between the HSIT and pressurizer is fixed at reactor trip for analysis. Therefore, future evaluation will focus on assessing accident progression based on different check valve opening timings to determine the optimal opening time.

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