Evaluation for Accident Mitigation Effect of External Injection at WH600 using MELCOR

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1. Introduction

After the Fukushima nuclear power plant accident, the lesson was learned for the risk of the beyond design basis external event (BDBEE). In most existing accident management systems, if the engineering safety system becomes unavailable due to the BDBEE, there were no separate facilities and procedures and the accident could progress to a severe accident [1]. Hence, a multi-barrier accident coping strategy (MACST) was established to prevent that BDBEE proceeds into a severe accident. The MACST consists of three phases: using the facilities installed in the plant initially, using the MACST equipment, and using the off-site facilities with the MACST equipment in the long term [1]. The MACST includes mobile equipment such as power generation vehicles, external injection pumps, heat exchangers, etc. [2]. Besides, existing guidelines are being improved and MACST operating guideline is being developed [3].

The effectiveness of accident mitigation strategies may differ depending on the action taken by the operator and the strategies for MACST equipment have not been systematically established. Hence, it is necessary to evaluate the mitigation effect according to the procedure of strategy. Therefore, in this study, accident mitigation performance is evaluated for the external injection pumps.

2. Methods

2.1 Plant Nodalization

The reference plant is selected as the Westinghouse 600 (WH600), which has the earliest commercial operation timing among nuclear power plants in Korea. The WH600 consists of 2 loops and each loop has a cold leg and hot leg [4]. The pressurizer has two power operated relief valves (PORV) and the main steam line of the steam generator has a pressure relief valve (PRV). These valves are controlled automatically or manually to protect the RCS and secondary system from over-pressurization by discharging the steam to the containment and atmosphere, respectively [4].

Figure 1 shows the RCS and core nodalization of the MELCOR model. As shown in Figure 1, the external injection pumps are highlighted with the blue line and they are connected to the cold leg B and secondary system of the steam generator B. When each system is lower than 1.96 MPa, the coolant is injected from the external pump to each system, respectively [2]. The core consists of 15 levels and 5 rings, and the active core is covered by 5 to 14 levels. While the lower plenum of the reactor pressure vessel (RPV) consists of 3 levels, the core support plate is allocated at the 4th level.

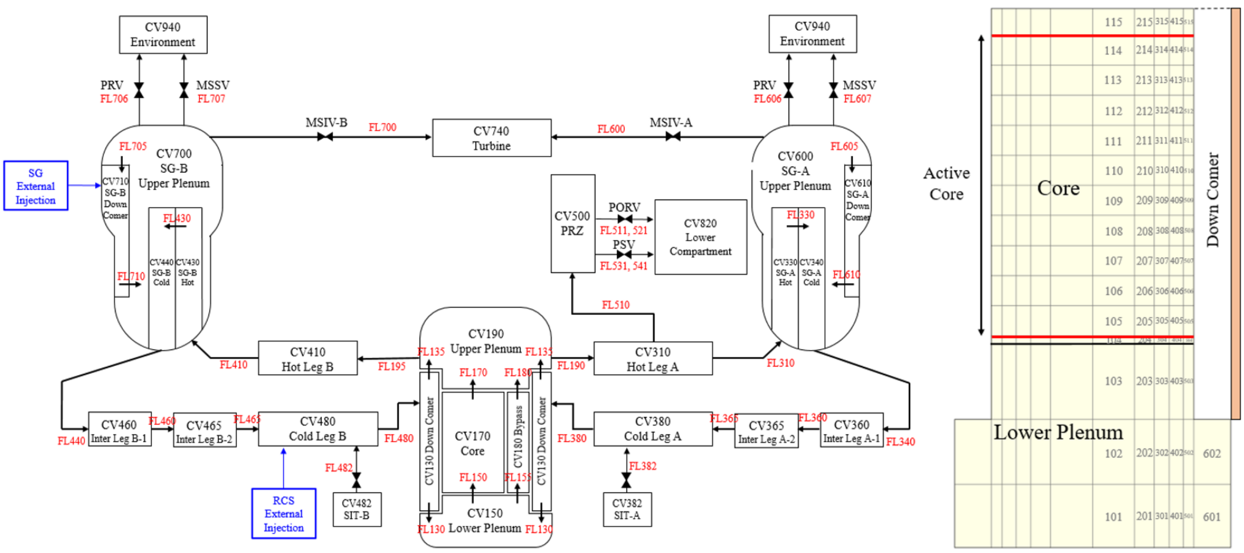

Fig. 1. Nodalization of MELCOR model (Left) RCS, (Right) Core

2.2 Accident Scenario

The reference accident scenario is assumed to be a loss of component cooling water (LOCCW) by an external event. The active safety systems equipped in the plant and turbine-driven auxiliary feedwater pumps are unavailable. The mobile external pumps are assumed to be available 1.5 hours after the initiating events occurred, and the PORVs and PRV are manually opened by the operator 30 minutes after the severe accident management guidelines (SAMG) entry condition [5]. The SAMG entry condition is met when the core exit temperature exceeds 649 °C [6].

Table I is a classification of the cases analyzed in this study. In the Base scenario, any actions are not taken by the operator. At Case 1, two PORVs are opened manually and only external injection to the RCS is possible, and at Case 2, both RCS and secondary external injections are available by opening the PORVs and PRV.

Table I: Classification of Accident Scenarios

	Base	Case 1	Case 2
Manually Opened Valve	-	2 PORVs	2 PORVs 1 PRV
External Injection Location	-	Cold Leg B	Cold Leg B SG B

3. Results

3.1 Accident Progression of Base Case

Table II: Accident Progression [hr]

Event	Base	Case 1	Case 2
Loss of CCW	0.00		
PRV Open	0.03		
PORV Open	1.20		
Mobile Pump Available	-	1.50	1.50
SAMG Entry Condition	2.18	2.18	2.18
Manually Valves Open	-	2.68	2.68
External Injection to SG	-	-	2.70
ACC Injection Start	3.11	2.90	2.80
ACC Injection End	3.12	2.91	3.11
External Injection to RCS	-	2.91	3.10
RPV Failure	3.10	3.93	-

Table II shows the accident progression of the cases. In the Base case, the RCS pressure reached the set point of PORV at 1.20 hours. The PORVs maintained the RCS pressure while repeating open and close, as shown in Figure 2. The coolant in the core leaked into the containment through the PORVs and the core exit temperature reached the SAMG entry condition at 2.18 hours. At 3.10 hours, the RPV failed and coolant was injected passively from the ACC due to the depressurization by the RPV failure.

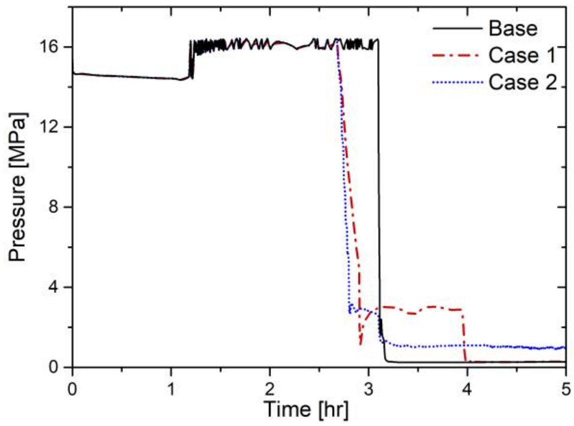

Fig. 2. RCS pressure

3.2 Effect of External Injection

In Case 1 and 2, the two PORVs were open manually by the operator at 2.68 hours and the RCS was depressurized. As shown in Figure 2, the pressure of the RCS decreased more rapidly in Case 2 than in Case 1, due to the heat removal by the secondary system. As a result, the coolant was injected from the ACC at 2.80 hours in Case 2, which was earlier than Case 1. When the coolant injection from the ACC was terminated, the coolant was injected from the external pump to the RCS at 2.91 and 3.10 hours, respectively, for each accident scenario. Figure 3 shows the flow rate of the external injection to the RCS. In Case 1, the RCS pressure was not sufficiently depressurized and the coolant was not injected continuously from the external pump. As shown in Figure 4, the core water level was not fully recovered to the top of the active core at Case 1. While at Case 2, the core water level was completely recovered from the beginning of the external injection.

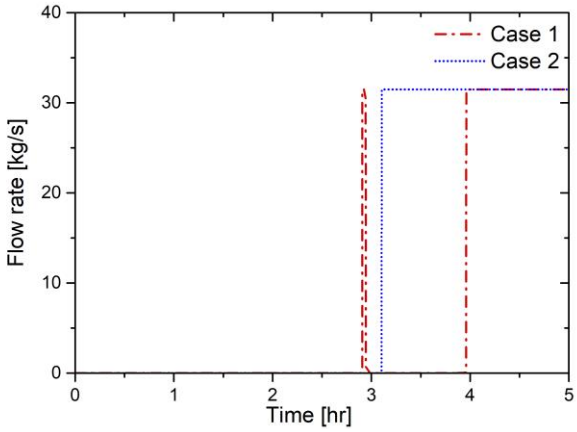

Fig. 3. Flow rate of external RCS pump

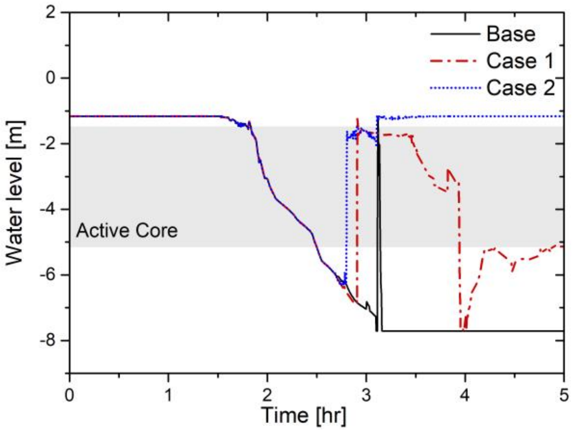

Fig. 4. Core water level

Figures 5 and 6 show the temperature of the supporting structure (SS) in the lower plenum. In 2.56 hours, the SS of cell 104 was exposed and the temperature of it gradually rose, and in 2.69 hours, the debris was relocated and the temperature rose rapidly. At Base and Case 1, the SS failed due to high temperature, and debris was easily relocated to the lower cell. As shown in Figure 6, the SS temperature of cell 103 rose rapidly due to the relocation of the debris. In Case 1, due to the external injection and ACC, the failure timing of SS in cell 103 was delayed by 0.5 hours from the Base. Accordingly, the RPV failed at 3.10 hours in the Base case, and at 3.93 hours in Case 1.

On the other hand, in Case 2, the residual heat was continuously removed by the secondary system and a large amount of coolant was rapidly injected into the RCS. Hence, the supporting structure maintained its integrity and the debris was not relocated to the bottom of the RPV.

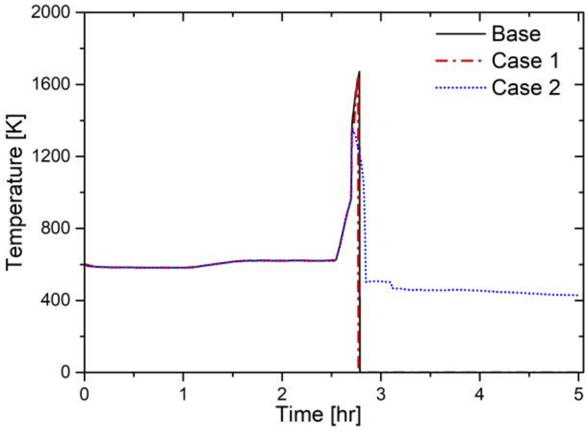

Fig. 5. Supporting structure semperature of cell 104

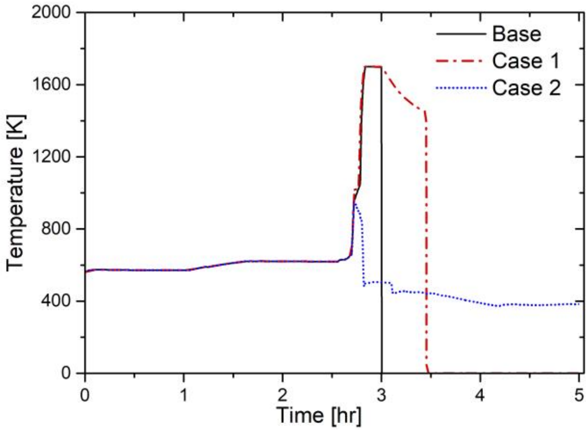

Fig. 6. Supporting structure temperature of cell 103

4. Conclusions

In this study, the accident mitigation effectiveness of the external injection was evaluated under a LOCCW event where the on-site safety systems were unavailable.

When any mitigation actions were not taken, the RPV failed at 3.10 hours such as the Base case. In Case 1, the timing of the SS failure was delayed compared to the Base case due to the external injection to the RCS and ACC. However, the depressurization with 2 PORVs was not enough, so a sufficient amount of coolant could not be injected by external injection to cool down the residual heat. As a result, the RPV failed at 3.93 hours in Case 1. In other words, the residual heat must be removed through the external injection to the RCS and secondary system at the same time to maintain the integrity of the RPV.

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