Analysis of External Injection Effects for Low-Pressure Mobile Pumps using MELCOR Code

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1. Introduction

Following the nuclear safety act revision in 2016, Korea Hydro & Nuclear Power Corporation (KHNP), a Korean nuclear power plant licensee, submitted an Accident Management Program (AMP) for all operating nuclear power plants to the Nuclear Safety and Security Commission (NSSC) in 2019 [1]. AMP includes a plan to utilize the Multi-Barrier Accident Coping Strategy (MACST), which is a new severe accident response strategy to deal with extreme hazard events. One of the MACST strategies is the external injection of emergency cooling water using low-pressure mobile pumps [2]. Cooling water outside the containment building can be injected into the Reactor Pressure Vessel (RPV), steam generators, and reactor cavity. Each path is utilized to perform the function of direct core cooling, secondary heat removal, and relocated corium cooling, respectively.

However, in the case of extreme hazard events or multi-unit accidents, the use of mobile equipment can be limited in the number of available equipment, external injection time, and injection path. In such a case, an appropriate decision making on how to utilize the equipment is required. To make optimal decisions, understanding the effects of mobile equipment is essential. Therefore, in this paper, the accident mitigating effects of start timing of the low-pressure mobile pump are analyzed.

2. Methods and Results

2.1 Reference Plant

APR1400 is selected as a reference plant. It is a two-loop pressurized light water reactor with thermal power of 3,983 MW. Each loop consists of one hot leg and two cold legs. Unlike other reactors in Korea, APR1400 has a refueling water storage tank inside a containment building, that is called In-containment Refueling Water Storage Tank (IRWST).

2.2 Accident Scenario

As a reference accident scenario, a long term Station Blackout (SBO) caused by extreme hazard events such as a major earthquake or tsunami is selected. In the scenario, it is assumed that all active safety systems are unavailable due to a failure of power recovery. In this case, the only water source available to cool down the core is the external injection using mobile pumps. This scenario makes it easy to analyze the effects of external injection since there is no other active safety systems are available.

In the reference accident scenario, it is assumed that only the passive safety systems work. The passive safety systems in APR1400 that can operate without electricity are Safety Injection Tank (SIT), Passive Autocatalytic Recombiner (PAR), IRWST gravitational drainage, and Steam Generator Turbine Driven Pump (SG TDP) [3].

The low-pressure mobile pump is used to supply the emergency cooling water from the outside of the containment to the inside when the Safety Injection System (SIS) is unavailable. The mobile pumps of the reference plant are kept in the integrated storage house, a separate storage area away from the plant, so as not to be affected by extreme hazards occurring at the plant [4]. The external water source can provide a sufficient flow for 72 hours (approximately 20 million liters). The strategy using the mobile pumps is presented in Severe Accident Management Guidance (SAMG) [5].

The RCS should be depressurized below 12.43 kg/cm^2A (1,219 kPa) for the external injection [6]. Therefore, the operator can open the Pilot Operated Safety Relief Valve (POSRV) before the external injection. The emergency cooling water is injected into the RPV downcomer.

However, excessive injection of water can flood the containment building and it causes the loss of essential equipment and monitoring capabilities. To avoid the flooding, the SAMG gives a graph of cooling water injection rate for long-term decay heat removal by limiting the rate of the water level rising in the containment building [7]. The graph defines the flow rate of the external injection. The injection rate is limited to 9.583 kg/sec since the SAMG entry time in the reference scenario is 15.34 hours after the reactor trip. The SAMG entry condition is met when the core exit temperature exceeds 922 K (1200 °F) [8].

As the utilization plan of the low-pressure mobile pump is presented in the SAMG, the sensitivity analysis is performed varying to the start time of the external injection after the SAMG entry [5]. The start time of the external injection is divided into 10 minute intervals from immediately after the SAMG entry into 60 minutes (from SAMG-0 to SAMG 60 cases).

2.3 Accident Analysis Tool

The MELCOR code version 2.2 is used to simulate the accident. MELCOR is a comprehensive analysis code that can simulate the severe accident progress of light water reactors [9]. Figure 1 shows the RCS nodalization input for APR1400. In order to reflect the geometry of the plant, the RCS is divided into several Control Volumes (CV). Each control volume is connected by Flow Paths (FL) to simulate the material and energy transfer under severe accident conditions. The containment failure mode is assumed to be a rupture due to the overpressurization, and the rupture pressure is 1,513.4 kPa(a) [10].

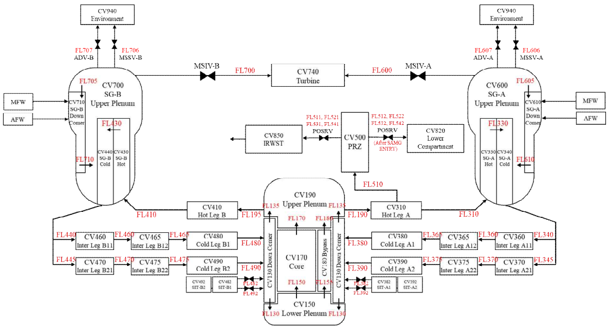

Fig. 1. MELCOR reactor coolant system nodalization for APR1400.

2.4 Results

As the external injection is delayed, the core could partially be damaged. Also, once the core begins to melt, the molten core can plug the coolant channel and therefore lose the coolable geometry. Then the RPV can be damaged even if the water is injected. After the molten core is relocated to the reactor cavity, the containment pressure increases due to the water evaporation and flammable gas generation by the Molten Corium-Concrete Interaction (MCCI). The containment will be ruptured if the pressure keeps increasing, and fission products can release to the environment.

The sensitivity analysis results are summarized in Table 1. Figure 2 shows the containment pressure behavior for each case. RPV is not failed in the SAMG-0 to SAMG-50 cases. As shown in Table 1, though the oxidation and evaporation in the core raise the containment pressure, the pressure does not reach the rupture pressure except for the SAMG-60 case.

In the SAMG-60 case, RPV failure occurs in 18.20 hours, and the molten core is relocated to the reactor cavity. Additional oxidation of corium and steam generation in the reactor cavity results in higher containment pressure than other cases. As a result, in 64.05 hours, the containment building ruptures and fission products release to the environment.

Figure 3 shows the state of the core structure after 72 hours. In the SAMG-0 case, fuel rods remain healthy. However, 10 minutes into the SAMG entry, the core is damaged even if the external injection is available. As the external injection time delays, more fuel melts. In the SAMG-60 case, the core melts more than the other cases, leading to the RPV failure.

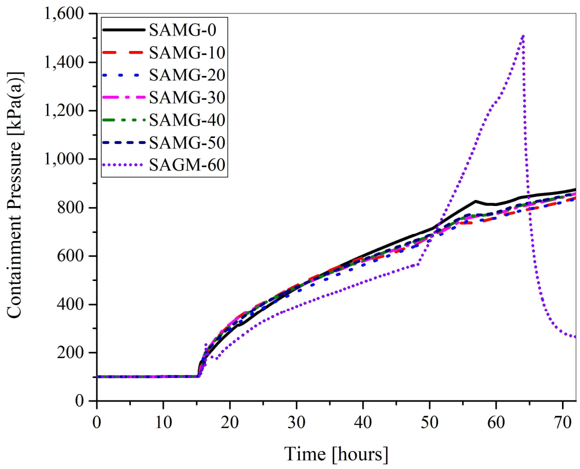

Fig. 2. Containment pressure behavior for 72 hours.

3. Conclusions

In extreme hazard events or multi-unit accidents, the use of mobile equipment can be limited. Therefore, it is necessary to analyze the accident mitigating effects of mobile equipment for various injection paths and accident scenarios. In this study, the accident mitigating effects varying to the start time of the low-pressure mobile pump in the long term SBO accident are analyzed. It is assumed that the emergency cooling water is injected into the RCS directly.

The external injection should be started at the same time as the SAMG entry to prevent the core damage. As the external injection delays, the molten core can block the coolant channels in the core. In that case, the core cannot maintain the coolable geometry. Even taking the risk of the core damage, the external injection should begin before 60 minutes into the SAMG entry to avoid the RPV failure. When the RPV is failed, the molten core is relocated to the reactor cavity, raising the containment pressure. If the pressure rise cannot be controlled, the containment will be ruptured.

From the results, the following insights into improving the SAMG and AMP strategy can be obtained:

- To avoid the core damage, the use of the low-pressure mobile pump should be included in the emergency operating procedures before the SAMG. Another option is to prepare the equipment to begin the external injection immediately after the SAMG entry.
- If the external injection is delayed more than 60 minutes after the SAMG entry, the ex-vessel core cooling strategies could be more effective than direct coolant injection into the core. In this case, it is also essential to restore the containment spray system for containment pressure control.

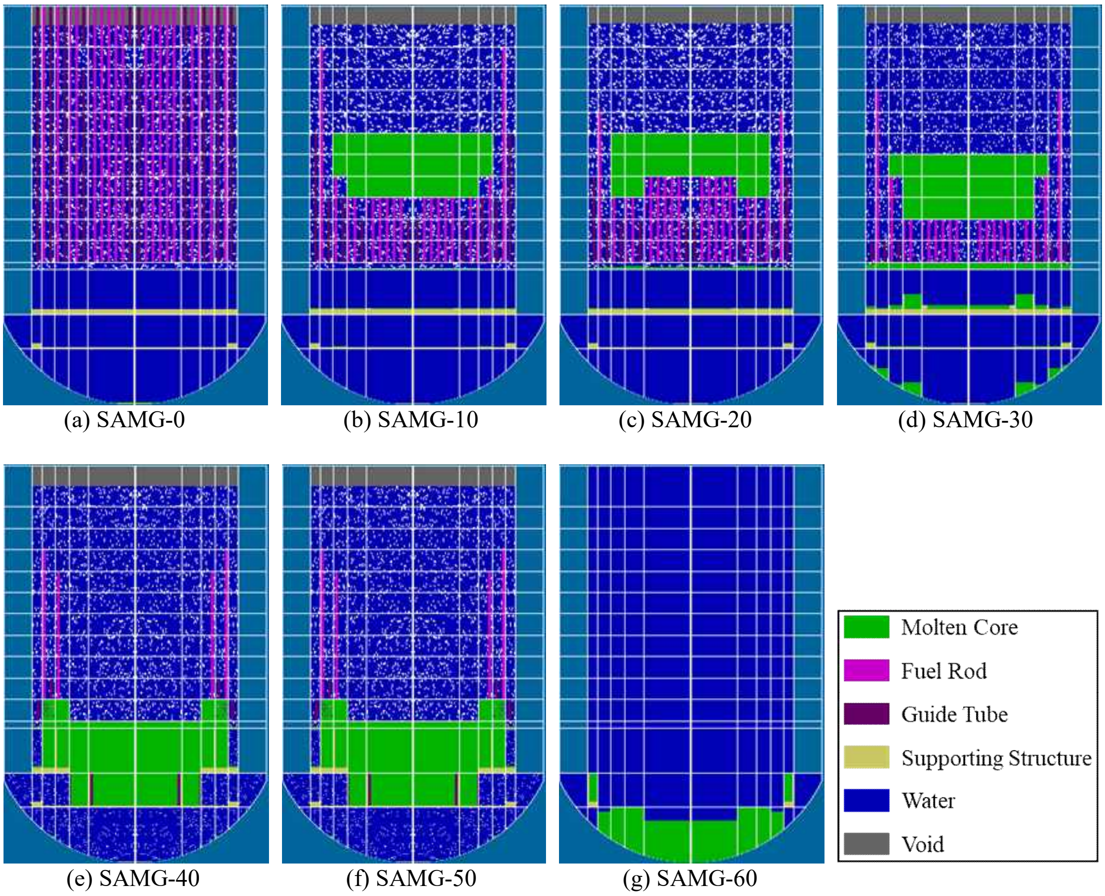

Fig. 3. Core degradation states 72 hours after reactor trip.

Table 1. MELCOR Simulation Results

Cases	SAMG Entry [hours]	External Injection [hours]	RPV Failure [hours]	Containment Failure [hours]	Containment Peak Pressure [kPa(a)]
SAMG-0		15.34	-	-	874.8
SAMG-10		15.51	-	-	840.3
SAMG-20		15.68	-	-	836.7
SAMG-30	15.34	15.84	-	-	858.0
SAMG-40		16.01	-	-	858.9
SAMG-50		16.18	-	-	860.9
SAMG-60		16.34	18.20	64.05	1513.4

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REFERENCES

[1] Nuclear Safety and Security Commission (NSSC), Regulation on the Scope of Accident Management and the Detailed Criteria for Evaluating Accident Management Capabilities, No. 2017-34, Notification, 2017.
[2] S. T. Yang, Current State of Accident Management Program Follow-up Measures. Accident Management Program and Stress Test Workshop, Transactions of the Korean Nuclear Society Autumn Meeting, Goyang, Korea, 2019.
[3] Korea Hydro & Nuclear Power Corporation (KHNP), Final Safety Analysis Report for Shin-Kori Unit 3&4, 2011.
[4] S. W. Hwang, Current State of KHNP-SOARCA Comprehensive Performance. KNNP SOARCA Technology Exchange Workshop, Transactions of the Korean Nuclear Society Autumn Meeting, Goyang, Korea, 2019.

[5] Korea Hydro & Nuclear Power Corporation (KHNP), Severe Accident Management Guidance for Shin-Kori Unit 3&4. Mitigation-03, 2015.
[6] Korea Hydro & Nuclear Power Corporation (KHNP), Severe Accident Management Guidance for Shin-Kori Unit 3&4. Mitigation-01, 2015.
[7] Korea Hydro & Nuclear Power Corporation (KHNP), Severe Accident Management Guidance for Shin-Kori Unit 3&4. Calculating Table -01, 2015.
[8] Korea Hydro & Nuclear Power Corporation (KHNP), Severe Accident Management Guidance for Shin-Kori Unit 3&4. Emergency-01, 2015.
[9] L. L. Humphries, B. A. Beeny, F. Gelbard, D. L. Louie, and J. Phillips, MELCOR Computer Code Manuals. Vol. 1: Primer and Users' Guide, Version 2.2.14959. SAND2019-12536 O. Sandia National Laboratories, 2019.
[10] Korea Hydro & Nuclear Power Corporation (KHNP), Probabilistic Safety Assessment Report for Shin-Kori Unit 3&4. Part 3. Containment Integrity Analysis, 2011.