Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

Simulation of Containment Behavior during a Station Blackout Accident in APR1400 Using MELCOR Code with Spray and PAR Models

Hyoung Tae Kim [*], Sang-Baik Kim, Jongtae Kim
Intelligent Accident Mitigation Research Division, KAERI, Daeduk-daero 989-111, Daejeon, Korea
[*]*Corresponding author: kht@kaeri.re.kr*

1. Introduction

In this study, in connection with the SPARC experiment [1], we have compared and evaluated the effects of the spray system on the operating nuclear power plant of APR1400. Various accident scenarios can be progressed depending on the severe accident conditions, and the Station Black Out (SBO) accident is selected for analysis of the MELCOR code. The Spray system operation in the containment building can affect the behavior of hydrogen removed by PAR at the same time as the inherent goal of fission product removal and pressure control in the containment building. Therefore, in performing MELCOR analysis for SBO accidents, it is necessary to consider the various actuation cases of the spray system with and without PARs.

The purpose of this study is to qualitatively and quantitatively evaluate the effects of the spray injection and PAR operation on pressure control and hydrogen combustion risk in the containment building of APR1400 nuclear power plant using the MELCOR code.

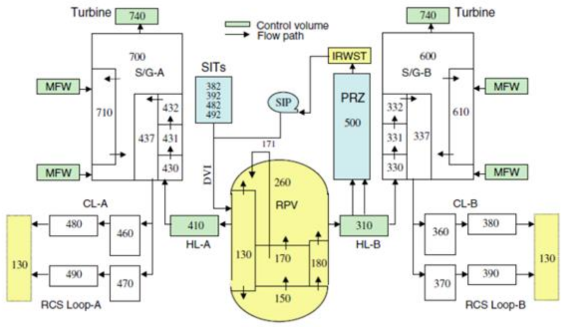
2. MELCOR Input Models

For MELCOR analysis for APR1400 nuclear power plants, containment building, spray systems, and PAR models should be added along with the thermal-hydraulic system models and severe accident analysis models. In this study, based on the existing MELCOR basic input model for APR1400, input models for analysis of major accidents in containment building were developed, and the progress of major accidents in the event of SBO accident was simulated.

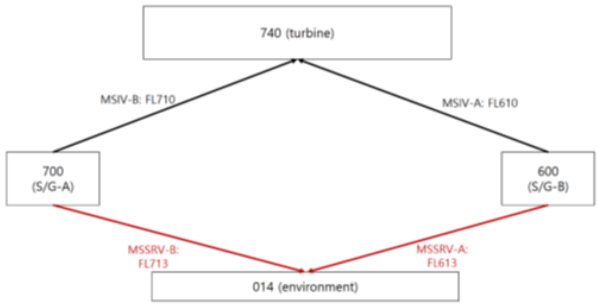
2.1 MELCOR Nodalization of APR1400

The basic input model of APR1400 used in this study is based on the report of the reference [2]. The nodaization for MELCOR analysis is shown in Figure 1.

The steam supply system, reactor building, and safety injection system of the APR1400 are simply modeled. It is composed of two primary coolant loops, each of which is composed of two reactor coolant pumps, one hot leg, and two cold legs. In addition, the pressurizer, the shell side of the steam generator, the main feed water system, the IRWST, the safety injection system, the main steam line, and the turbine boundary area are also simulated.



(a) Control Volumes and Flow Path in RCS model



(b) Secondary side model

Fig. 1. Nodalization of APR1400 for MELCOR Analysis.

2.2 Accident Scenario

According to the results of the PSA evaluation of the reference nuclear power plant [3], accidents with high core damage frequency are caused by initial events such as LOCA, secondary water supply loss, and plant power outage (SBO). The progress of accidents by these major early events can include high-pressure and low-pressure accidents, transition accidents, and power loss accidents.

In the case of the SBO accident, the basic accident adopted in this study, it starts with all emergency diesel generators failing and all off-site power being lost at the same time. Thereafter, most active safety systems that perform safety functions cannot be used because there is no alternative current AC power source. In particular, since the operation of the spray system and PAR is likely to have a significant impact on the hydrogen concentration in the containment building, various operating conditions of these safety systems were combined and considered in the selection of accident scenario.

The SBO accident assumed that the safety system of the containment building that requires power was not operated in the initial SBO accident, but the no power source was restored for a certain period of time and after that the spray system could be operated. In other words, based on the time of the severe accident entry conditions, the spray system operates after a certain period of time (1, 2, 3, 4 hours later).

Table 1 summarizes the SBO accident scenarios with operation of PAR and spray.

Table 1 Accident Scenarios of PAR and Spray Actuations

Case	PAR & Spray Actuation
Case A (base case)	Only PAR Actuation
Case A0	at SAMG Entry Point
Case A1	at 1 hour after SAMG Entry Point
Case A2	at 2 hour after SAMG Entry Point
Case A3	at 3 hour after SAMG Entry Point
Case A4	at 4 hour after SAMG Entry Point

2.3 Calculation Results

MELCOR [4] analysis was performed by applying spray injection conditions with reference to spray system design parameters for Sinuljin Units 1 and 2 of APR1400 nuclear power plant.

The SBO accident is an accident in which all on-site and off-site power is lost, and all safety systems except the safety system are shut down. As shown in Table 1, when SBO starts at 0 second, the primary system pump is stopped and the reactor is stopped. As feed water supply to the steam generator secondary side is stopped, the water level of the steam generator secondary side is dropped and exhausted, and thus the temperature and pressure at the primary side are increased, such that a safety relief valve (SRV) is first opened at about 3,600 seconds. Due to cooling water loss through SRV, the cooling water level in the reactor decreases and core exposure occurs, and the steam temperature at the core outlet reaches 923 K at about 8,600 seconds, entering the Severe Accident Management Guideline (SAMG). Upon entry into the SAMG, the operator depressurizes the reactor's primary system, and steam emitted through the ADV (Automatic Depression Valve) is then discharged directly to the atmosphere of the containment building through the Steam Dump Line.

In the APR1400 nuclear power plant, steam emission through ADV at the same time as the start of SAMG increases the pressure to the high pressure setting of the containment, so Case A0 may be considered almost similar to the case by a spray injection signal.

Case A is a case in which only PAR is operated without spraying operation, and compared to Case A0, where spraying is operated, the accident proceeds at almost the same time until 8,780 seconds, then the core melts, relocates, and the bottom of the reactor is damaged. Finally, when comparing the reactor vessel failure times, it was found that Case A, in which only PAR operates, occurs 19,303 seconds, while Case A0 with spray injection occurs 17,222 seconds earlier than 2,000 seconds. It can be seen that water injection in the containment building has the effect of promoting the progress of serious accidents in the reactor.

One peculiarity is that in the cases of Case A where spray is not injected, Case A3 and Case A4, where spray injection is delayed by 2 hours or 3 hours, the accident development proceeds equally until this time because the spray injection time does not occur until the reactor vessel is failed.

Table 2 Accident Progress of SBO cases

Event (calculation message)	Case A (PAR)	Case A0 (PAR & Spray)	Case A3 (PAR & Spray)
RCP TRIP	-0.2	-0.2	-0.2
REACTOR TRIP	0.2	0.2	0.2
CFS VALVE OPEN / IRWST-HVT VALVE OPEN	99.9	99.9	99.9
SG-LOOP1 DRYOUT	3,645.0	3,645.0	3,645.0
SRV(PRZ) IS OPEN FIRST	5,524.3	5,524.3	5,524.3
START CORE UNCOVERED : WATER-LEVEL=-1.55 M	7,586.7	7,586.7	7,586.7
SAMG Entry Condition / Dump Line Change	8,602.2	8,602.2	8,602.2
CORE DRYOUT : WATER-LEVEL=-5.4922M	8,778.0	8,778.0	8,778.0
START TO INJECTION SIT-392	8,780.0	8,780.0	8,780.0
SIT-392 : INVENTORY EXHAUSTED	9,624.3	9,538.8	9,624.3
CORE SUPPORT STRUCTURE (PLATE) HAS FAILED IN CELL 113, FAILURE WAS BY OVERTEMPERATURE	12,903.6	12,304.2	12,903.6
START TO MELT FUEL	13,104.5	12,515.1	13,104.5
START OF DEBRIS QUENCH IN RADIAL RING 1	17,469.9	15,854.5	17,469.9
UO2 RELOCATED TO LOWER HEAD	18,918.4	17,008.9	18,918.4
LOWER HEAD PENETRATION 3 IN SEGMENT 3 OF RADIAL RING, INITIAL DIAMETER OF HOLE IS 1.520E-01 M	19,302.5	17,222.3	19,302.5

In Figure 2, we investigated how the trend of the pressure of the containment building was affected by varying the timing of spray injection. Four cases in which the spray operation is delayed every hour were simulated as well as the reference case A, and it can be seen that even if the spray operation starts 4 hours after the time of reaching SAMG (Case A4), the pressure of the containment building is stably low, such as when the spray is injected earlier than that.

Figure 3 shows the change in hydrogen mole fraction. The hydrogen fraction continues to increase as hydrogen generated by damage of the core is released into the containment atmosphere through ADV after entering the SAMG. Hydrogen is continuously released by MCCI after reactor vessel damage occurs, but when hydrogen concentration increases above a certain level, hydrogen recombination by PAR occurs and the hydrogen mass decreases gradually in the long run. As shown in Figure 3, when spraying water is not injected, the amount of steam increases relatively, and the decrease in hydrogen fraction is more pronounced.

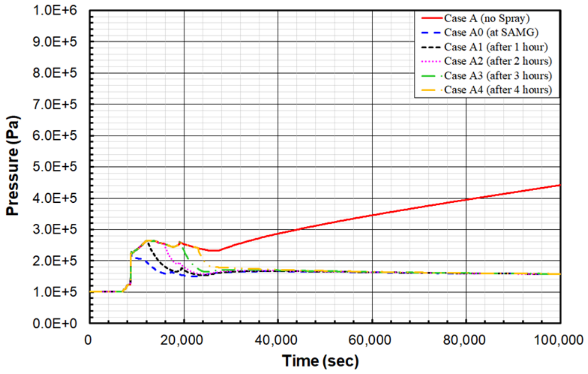


Fig. 2. Comparison of containment pressures for different cases of spray injection.

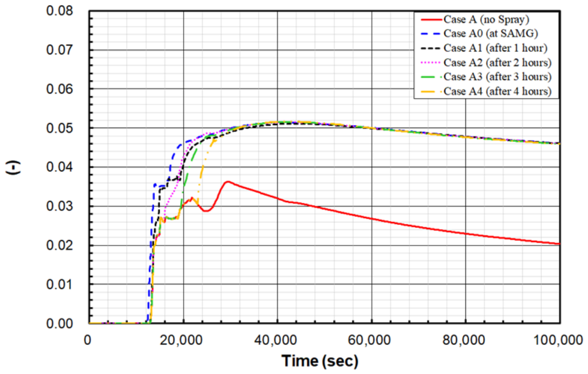


Fig. 3. Comparison of hydrogen mole fractions for different cases of spray injection

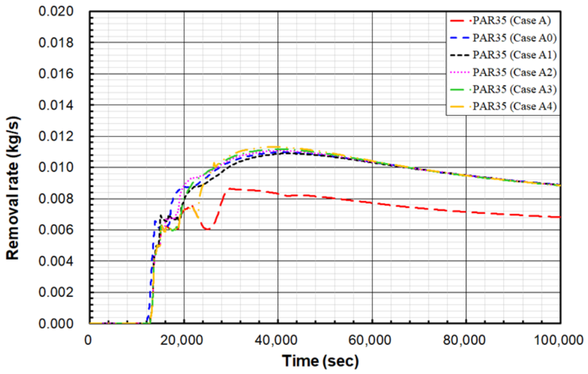


Fig. 4. Comparion of hydrogen removal rate by PARs for different cases of spray injection.

In Figure 4, the change in the hydrogen removal rate in the upper dome of the containment building was compared for different spray operation times. All of the cases where spray is injected show almost the same change in hydrogen removal rate, but Case A, where spray is not injected, shows a lower change in hydrogen removal rate than these are the only cases. This is because the hydrogen fraction becomes relatively low when spraying water is not injected, so the hydrogen removal rate is also calculated lower based on the hydrogen removal rate correlation equation. Therefore, it can be seen that the change in the hydrogen removal rate is quite similar to the change in the hydrogen fraction in Fig.3.

3. Conclusions

Since the release of steam through the SRV of the reactor system at the beginning of the SBO accident is made by IRWST, there is little change in the containment pressure, and when the SAMG entry condition is reached, the containment pressure rises rapidly due to the decompression of ADV and atmospheric discharge of the containment. Shortly thereafter, the high pressure set point of the containment building, which is the operating condition of the water spraying system, is reached. In the course of the SBO accident, the spray system could not be operated due to the loss of initial power, but it was assumed that the external power could be restored during the accident and the spray system could be operated. As a result of the analysis, when only PAR is operated or the spray system is operated in an appropriate time, hydrogen combustion/control in the containment building and pressure control due to water spraying are performed in combination, thereby maintaining the integrity of the containment building. The results of simulating the cases in which the spray system operates at a time lag of up to 4 hours every 1 hour from the time of arrival of the SAMG can be a reference for establishing a SAMG strategy for SBO accidents.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT, and Future Planning) (No. 2012M2A8A4025889)

REFERENCES

[1] 김형태, 김종태, SPARC 실험장치에서의 살수실험에 대한 MELCOR 코드 해석, KAERI/TR-7862/2019, KAERI, 2019.

[2] Vo thi Huong, MELCOR APR1400 Input Report 1, Rev. 01, June 2015.

[3] 한국전력기술, "신한울 1,2 호기 중대사고분석보고서", Rev.0.

[4] R.O. Gauntt et. al., MELCOR Computer Code Manuals, Version 1.8.6, Users Guide and Reference Manual, NUREG/CR-6119, SAND2005-5713, U.S. Nuclear Regulatory Commission, 2005.