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MELCOR assessment of sequential severe accident mitigation actions under SGTR accident

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1. Introduction

Since the severe accident occurred in Fukushima in 2011, various researches regarding the severe accident have been investigated experimentally and numerically. Many experiments for understanding the severe accident phenomena were performed and the results were used to confirm the safety of nuclear power plants. However, most of the experiments dealing with the severe accident phenomena are technically difficult to perform. Rather abundant studies focus on development of reliable prediction methodology using severe accident code. The representative example of the severe accident studies using the severe accident code is investigation of effectiveness of developed severe accident management (SAM) strategy considering the positive and adverse effects.

In Korea, some numerical studies were performed to investigate the SAM strategy using various severe accident codes. Park et al. [1] investigated the effect of a coolant injection into the reactor vessel with depressurization of RCS strategies under the SBLOCA using the SCDAP/RELAP5. More recently, Lee et al. [2] and Seo et.al [3] performed validation of RCS depressurization strategy and investigated the effect of severe accident management guidance (SAMG) entry condition under small break loss of coolant accident (SBLOCA) without safety injection (SI), station blackout (SBO), and total loss of feed water (TLOFW) scenarios. However no detailed analysis was conducted for representative containment bypass accident such as steam generator tube rupture (SGTR).

As mentioned earlier, many studies investigated the effect of mitigation strategies depending on the kind of actions and its timing. However, most of studies focused on individual mitigation strategies and assumed arbitrary delay time between the mitigation actions. From these points, the sequential mitigation actions according to the flow chart in SAMG were simulated by the MELCOR code. Two scenarios which prevented the RPV failure were identified by the MELCOR calculations and the modified sequences of mitigation actions were suggested. The calculation results were analyzed and presented in terms of reactor pressure vessel (RPV) failure, fission product release, hydrogen risk, and containment pressure.

2. Numerical methods

2.1 MELCOR input model of OPR1000

MELCOR nodalization of optimized power reactor 1000 MWe (OPR1000) is shown in Fig.1. The input model consists of reactor coolant system (RCS), Steam generators (SGs), and containment. The RCS includes two hot legs, four cold legs, RPV, and pressurizer. The pressurizer safety relief valve (PRSV) and safety depressurization system (SDS) valve are located at the top of the pressurizer to control the RCS pressure. Since OPR1000 is a two-loop plant, the input model includes two SGs. Atmospheric dump valve (ADV), condenser dump valve (CDV), and main steam safety valve (MSSV) are modeled at the top of each SG. To simulate the release of coolant by SGTR, flow path (FL) 336 was modeled from SG tubes of loop A (CV330) to the SG of loop A (CV600). The flow area of FL336 was selected 4.49E-4 m^2, which is double of one SG tube area, to simulate the guillotine break of one SG tube.

2.2 Description of SGTR accident

To simulate the severe accident initiated by the SGTR, the result from the probabilistic safety analysis (PSA) Level 1 report was used to define the accident scenarios. For the MELCOR simulation, following assumptions were applied.

- Accident started with the guillotine break of one SG tube.
- Before SAMG entrance, the operator failed in depressurizing RCS and activating the high pressure safety injection (HPSI)
- Auxiliary feed water system (AFWS) was unavailable and recovery of AFWS was conducted 1 hour after the SAMG entrance.

2.3 Description of mitigation strategy

According to the SAMG, the mitigation strategies were applied sequentially by the flow chart as shown in Figure 2. To perform the subsequent mitigation actions, the safety parameter of performing mitigation actions needs to satisfy the criteria of mitigation strategies. To simulate this process of sequential mitigation actions by the flow chart, repetitive MELCOR calculation was performed with useful information from Jin et al.'s study [4]. As a result, two mitigation scenarios according to the depressurization measures were defined as follows.

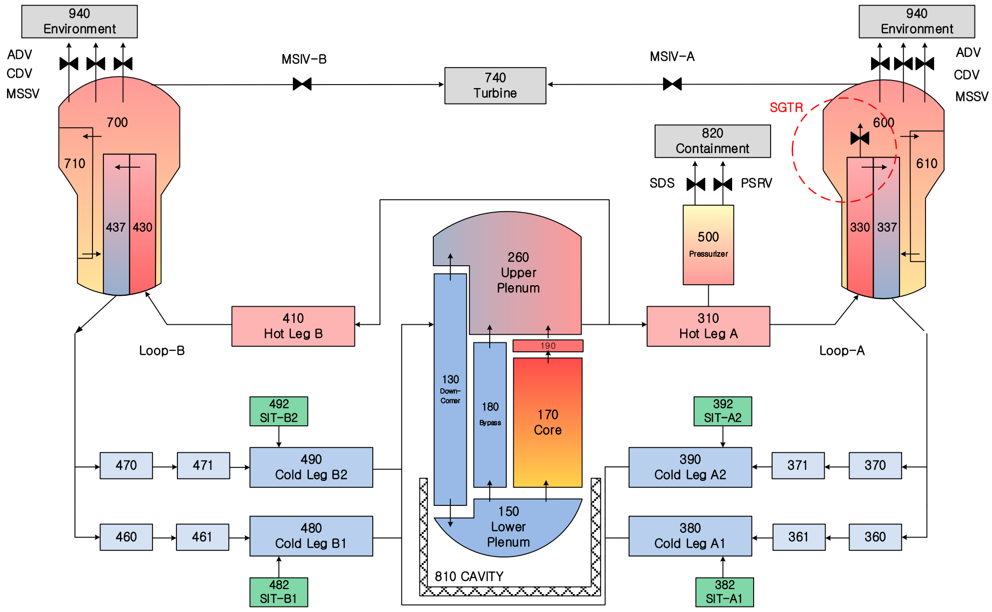

Fig. 1. MELCOR nodalization of OPR1000

- **Scenario 1**: SAMG entrance → Injecting into the intact SG → Injecting into the broken SG → Opening one ADV of intact SG

- **Scenario 2**: SAMG entrance → Injecting into the intact SG → Injecting into the broken SG → Opening one valve of SDS → Activate HPSI

Table I shows the timing of mitigation actions and each set point of safety parameters.

Table I: The timing of mitigation actions and each set point of safety parameters

Accident Sequence (Set points)	Scenario 1	Scenario 2
	Time (hr)	
SAMG entrance (CET = 923 K)	3.25	3.25
Injecting into the intact SG (SG WR > 63 %)	4.25	4.25
Injecting into the broken SG (SG WR > 63 %)	5.37	5.37
Depressurization RCS (RCS pressure < 2.86 MPa)	6.60	6.60
Activate HPSI (CET < 623 K)	N/A	9.48

3. Results and Discussion

3.1 The progress of sequential mitigation actions

To simulate the sequential mitigation actions according to the flow chart of SAMG, the safety parameter of the MELCOR calculation results was checked out. When the safety parameter of current mitigation strategy was satisfied, the operator actions of next mitigation strategy were applied.

Fig. 2 shows the SG water level with injecting into SG. When the accident condition reached the SMAG entry condition at 3.25 hours, all of the SG water level was below the set point of mitigation-01: Injecting into the SGs. To apply the mitigation-01, AFW pumps were recovered and feed water was injected into the intact SG 1 hour after the SAMG entrance. At 5.37 hours, the water level of the intact SG reached the set point of mitigation-01 and subsequent feed water injection was performed to the broken SG. As a result of feed water injection, all of SG water was recovered above the set point of mitigation-01 at 6.60 hours.

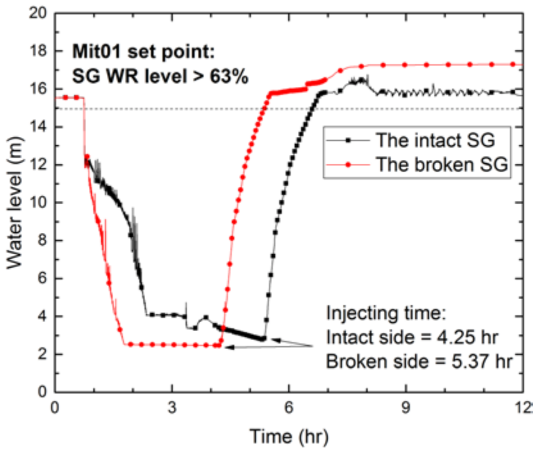

Fig. 2. SG water level of the case with injecting into SG

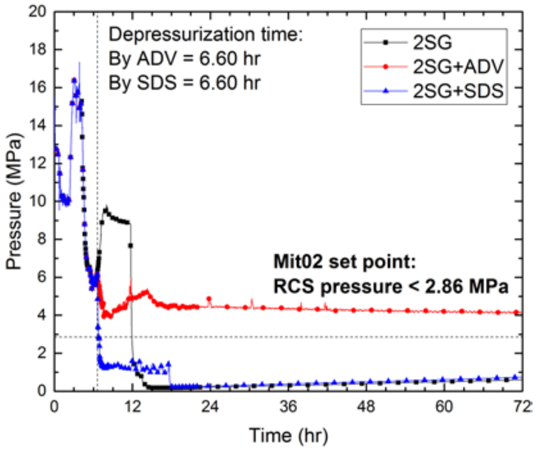

Fig. 3. RCS pressure of the case with RCS depressurization

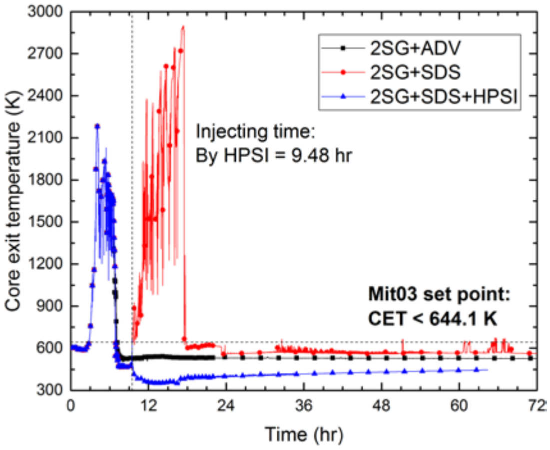

Fig. 4. CET of the case with injecting into RCS

Fig. 3 shows the RCS pressure with depressurization. After the safety parameter of mitigation-01 satisfied the set point at 6.60 hours, mitigation-02: Depressurization RCS was applied. The RCS pressure decreased rapidly by the cooling of the steam when indirect depressurization using the ADV of intact SG was performed at 6.60 hours. However, the minimum RCS pressure during 72 hours was above the set point of mitigation-02. In the case of direct depressurization using SDS, the steam in the RCS was released into the containment and the RCS pressure decreased rapidly. As a result, the RCS pressure decreased below the set point of mitigation-02 at 6.82 hours.

Fig. 4 shows the core exit temperature (CET) for the case with injecting into RCS. When the indirect depressurization using ADV was performed, the heat removal by the SG was enhanced due to the increase of releasing steam. By the enhanced heat removal of SGs, the heat from the core was sufficiently removed. As a result, CET was maintained below the set point of mitigation-03: injecting into RCS. When the direct depressurization by SDS was performed, the coolant in the RCS was released into the containment. The released coolant caused uncovering of the core. As a result, the core cooling by SGs was interrupted by the lack of the coolant and the CET was reached to the set point of mitigation-03 at 9.48 hours. To decrease the CET below the set point of mitigation-03, the injecting into RCS by HPSI was applied at 9.48 hours. For the case with injecting into RCS by HPSI, the CET decreased rapidly after the injection by HPSI and maintained below about 500 K.

3.2 The comparison of major parameter

The accident with operator actions were simulated according to the Scenario 1 & 2. Total five simulations were calculated according to the set point of safety parameter. Table III shows the major parameter with mitigation actions. When the injecting into SGs was performed, the RPV failure was delayed about 3 hours and 6 hours depending on the number of injected SGs. The released cesium mass with injecting both SGs decreased to 1.3 kg due to the pool scrubbing effect of the broken SG. However, the released cesium mass with injecting into one SG was increased. When the opening ADV of intact SG with injecting into both SGs (Scenario 1) was performed, the core degradation was prevented. When SDS valves were opened after injecting into the both SGs, the core degradation was observed by the release of coolant. Nevertheless, decrease of RCS pressure initiated the safety injection tank (SIT) and thus the RPV failure was delayed by approximately 12 hours. In the additional mitigation action by injecting RCS after opening the valve of SDS (Scenario 2), injected coolant continuously removed the core heat and the RPV failure was prevented until the end of the calculation. However, the containment pressure increased up to 0.674 MPa due to the released steam from the RCS. When the mitigation actions mitigated the core degradation and prevented RPV failure (Scenario 1 & 2), the hydrogen concentration maintained below the criteria for the termination of SAM.

3.3 Modified sequence of mitigation actions

To reduce the released cesium mass during the SGTR accident, modified sequence of mitigation actions was suggested in this study. The modified sequence suggests mitigation strategies according to the following scenario.

- **Scenario 3**: SAMG entrance → Opening one valve of SDS → Closing the valve of SDS → Injecting into the intact SG → Injecting into the broken SG → Opening one ADV of intact SG

Table III shows the results of the modified sequence of mitigation actions. In Scenario 1 & 2, the injecting into SGs was performed first. During injecting into SGs, the RCS pressure remained higher than that of the SGs and the fission products were released into the environment continuously before the depressurization. In Scenario 3, depressurization RCS by SDS was

Table II. Major parameter of the case with mitigation actions

Major parameter	Base	Mit01 (1SG)	Mit01 (2SG)	Mit01+02 (ADV)	Mit01+02 (SDS)	Mit01+02 (SDS) +03
	Time (hr)					
RPV failure	5.41	8.57	11.73	**No failure Scenario1**	17.63	**No failure Scenario2**
The released cesium mass (kg)	8.966	14.423	7.420	**7.375**	7.374	**7.374**
The hydrogen risk (mole fraction)	0.0694	0.0744	0.0524	**0.0105**	0.0457	**0.0238**
The containment pressure (MPa)	0.656	0.595	0.607	**0.123**	0.749	**0.674**

performed before injecting into the SGs. To reduce the adverse effect from actuation of SDS, the valve of SDS was closed at 4.51 hours. Subsequently, injecting into SGs were performed in the order of intact and broken SGs.

After injecting into both SGs, one ADV of intact SG was opened at 7.11 hours to enhance the heat removal by the intact SG. As a result, the released cesium mass decreased about 1.3 kg and RPV failure was prevented. Although the release of steam was observed due to SDS operation, containment pressure only increased to 0.44 MPa, which is lower than the results in Scenario 2. Hydrogen mole fraction in Scenario 3 was higher than that of Scenario 1 & 2. Nevertheless, the hydrogen mole fraction of the Scenario 3 was below the criteria for the termination of severe accident management.

Table III: The results of modified sequence of mitigation actions

Accident Sequence	Scenario		
	1	2	**3**
	Time (hr)		
SAMG entrance	3.25	3.25	**3.25**
Injecting into the intact SG	4.25	4.25	**4.51**
Injecting into the broken SG	5.37	537	**5.65**
Opening ADV	6.60	N/A	**7.11**
Opening SDS	N/A	6.60	**4.25**
Activate HPSI	N/A	9.48	**N/A**
RPV failure	No failure	No failure	**No failure**
The released cesium mass (kg)	7.375	7.374	**6.023**
The hydrogen risk (mole fraction)	0.0105	0.0238	**0.0338**
The containment pressure (MPa)	0.123	0.674	**0.234**

3. Conclusions

The SGTR accident with the sequential mitigation actions according to the flow chart of SAMG was simulated by the MELCOR 1.8.6 code. Three scenarios preventing the RPV failure were investigated in terms of fission product release, hydrogen risk, and the containment pressure. Major conclusions can be summarized as follows:

(1) According to the flow chart of SAMG, RPV failure can be prevented depending on the method of RCS depressurization.

(2) To reduce the release of fission product during the injecting into SGs, a temporary opening of SDS before the injecting into SGs was suggested. These modified sequences of mitigation actions can reduce the release of fission product and the adverse effect of SDS.

ACKNOWLEDGMENTS

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