Effect of In-Vessel Retention Strategies under Postulated SGTR Accidents of OPR1000

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1. Introduction

Since the Fukushima accident occurred in 2011, many countries operating nuclear plants have invested much effort to prepare for the severe accidents. Many researches related to severe accident analysis have been performed experimentally and numerically for the purpose of ensuring safety of the nuclear power plants. As well, in Korea, many experimental and analytical activities have been performed to investigate the thermal-hydraulic response of the Korean Optimized Power Reactor (OPR1000) against the postulated severe accidents. According to the probabilistic safety analysis (PSA) Level 1 of OPR1000, typical severe accident scenarios of high probability of a transition to severe accident for OPR1000 were identified as Small Break Loss of Coolant Accident (SBLOCA), Station Black out (SBO), Total Loss of Feed Water (TLOFW), and Steam Generator Tube Rupture [1]. While the first three accidents are expected to result in the generation and transportation of the radioactive nuclides within the containment building as consequence of the core damage and subsequent reactor pressure vessel (RPV) failure, the latter accident scenario may be progressed with possible direct release of the radioactive nuclides to the environment by bypassing the containment building. Thus it is of significance to investigate the SGTR accident with a sophisticated severe accident code.

In fact, simulating severe accidents requires a sophisticated tool containing numerous physical models related to severe accident phenomena such as fuel melting, oxidation, relocation, reactor pressure vessel failure, molten core concrete interaction, direct containment heating, hydrogen behaviors, to mention a few. Some integrated codes were designed and developed to undertake the simulation of the severe accidents and examples are MAAP, ASTEC, MELCOR, and SPECTRA. In this study, MELCOR code was used to simulate the severe accident of the OPR1000. MELCOR code is computer code which enables to simulate the progression of the severe accident for light water reactors. It has been developed by Sandia National Laboratories for plant risk assessment and source term analysis since 1982. This code can simulate the whole phenomena of a severe accident such as thermal-hydraulic response, core heat-up, oxidation and relocation, and fission product release and transport [2].

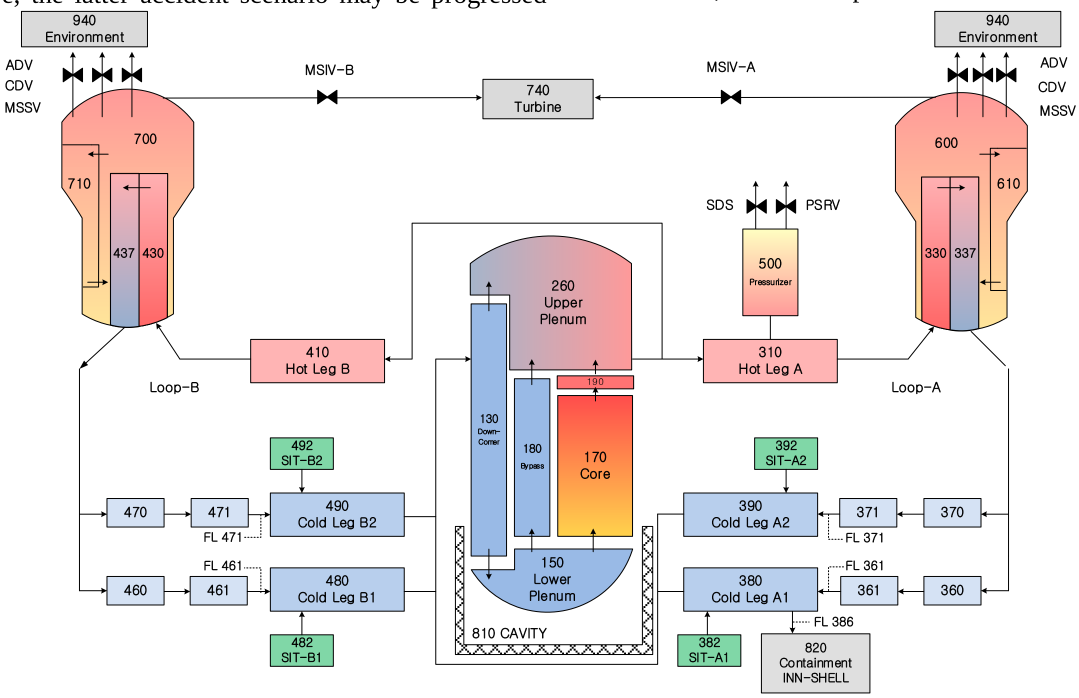

Fig. 1. Nodalization of MELCOR input model for OPR1000

Thus many researchers have used MELCOR in severe accident studies [3-5].

In this study, in-vessel retention strategies were applied for postulated SGTR accidents. Mitigation effect and adverse effect of in-vessel strategies was studied in aspect of RPV failure, fission product release and containment thermal-hydraulic and hydrogen behavior.

2. Numerical methods

2.1 MELOCR Description and input model of OPR1000

OPR1000 was selected for MELCOR simulation. Fig. 1 shows a nodalization of the OPR1000 used as a MELCOR input. The input model includes two steam generators (SGs), two hot legs, four cold legs, RPV and pressurizer. Fig. 2 shows the core nodalization of OPR1000 for MELCOR. The core consists of seven radial rings and fourteen axial levels. First axial level to third axial level are dedicated to lower plenum (CV 150) and fourth axial level to fourteenth axial level are dedicated to core region (CV170).

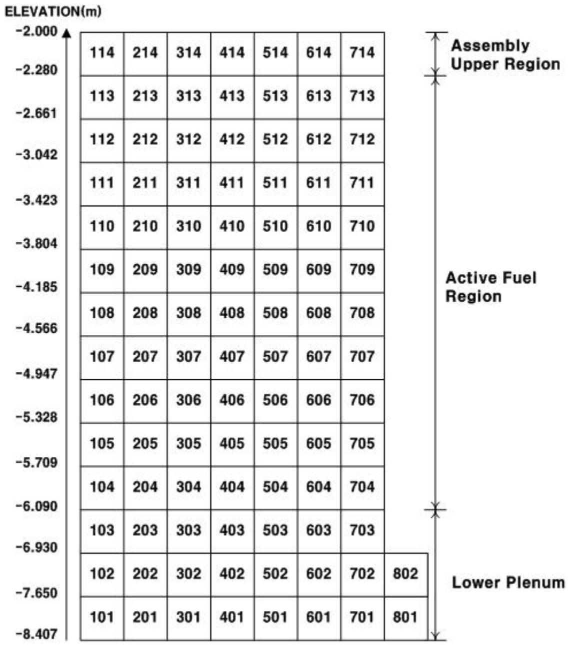

Fig. 2. The core nodalization of OPR1000 for MELCOR

II.B. Description of SGTR accident

2.2 Description of SGTR accident

To investigate SGTR accident as severe accident, the scenario of high probability of a transition to severe accident were selected according to the recent probabilistic safety analysis (PSA) Level 1 of OPR1000. The events of the scenario are as follows.

· Guillotine break of one steam generator tube
· Reactor trip by low pressure signal
· Fail to high pressure safety injection (HPSI)
· Fail to depressurize reactor coolant system (RCS)

With mentioned scenario, it was assumed that HPSI pump, auxiliary feed water (AFW) pump are unavailable for safety injection and depressurize of RCS.

2.3 Description of mitigation strategy

To investigate mitigation effect and adverse effect, steam generator (SG) feed water injection (Mitigation 1), reactor coolant system (RCS) depressurization (Mitigation 2), RCS coolant injection (Mitigation 3) were selected as mitigation strategy. Although AFW pump and HPSI pump were not available with base case assumption, it assumed that operator recovered these AFW pump or HPSI pump as a part of individual mitigation strategy. In case of recovering AFW pump, injecting feed water (Mitigation 1) and opening one ADV valve (Mitigation 2) is applied for the mitigation action. In case of recovering HPSI pump, HPSI pump injects coolant to RCS (Mitigation 3). In case of recovering none of AFW pump or HPSI pump, opening one pilot-operated relief valve (PORV) of safety depressurization system (SDS) is selected for operator's action (Mitigation 2). Table I. shows summary of all cases.

Table I. Summary of mitigation cases

Case	Mit-01	Mit-02	Mit-03
Mitigation strategy	1&2	2	3
Mitigation component	ADV +AFW	SDS	HPSI
Need to recover	AFW	None	HPSI

3. Result and discussion

3.1 Base case

Table II shows initiating time of several significant sequences for SGTR accident. After accident start, RCS coolant was released to the broken SG through the broken SG tube and the RCS pressure decreased slowly. The reactor trip initiated at 0.74 hours by low pressurizer pressure signal. Main feed water (MFW) pump stop and main steam isolation valve (MSIV) closure occurred at the same time as the reactor trip. Main steam safety valve (MSSV) which is operated at 8.61MPa was opened first at 0.75 hours. And Reactor coolant pump (RCP) tripped by the cavitation of pumps at 0.75 hours. The intact SG water dried out below 1000kg (1.77 hours) but the broken SG dryout delayed because of the break flow of SG tube (5.43 hours). The core exit temperature (CET) starts to increase rapidly and reached to 922K which is the severe accident management guidance (SAMG) entry condition at 3.35

hours. Onset of gap release was 3.43 hours and cladding and UO2 melt were 3.78 hours and 3.80 hour, respectively. RPV failure was initiated by lower head penetration at 5.62 hours. Fig. 3 shows RCS and SGs pressure and Fig.4 shows core exit temperature.

Table II. Significant sequences of SGTR accident

Accident Sequences	SGTR base Time (hr)
Accident Start	0
Reactor trip	0.74 (2679 sec)
MFW trip	0.74 (2679sec)
MSIV closure	0.74 (2679sec)
MSSV open	0.75 (2685 sec)
RCP trip	0.75 (2699sec)
Intact SG dryout	1.77
SAMG entrance	3.35
Oxidation start	3.38
Gap release	3.43
Cladding melt	3.78
UO2 melt	3.80
PSRV open	3.80
Core dryout	3.84
Melt relocation	3.95
Broken SG dryout	5.43
RPV failure	5.62

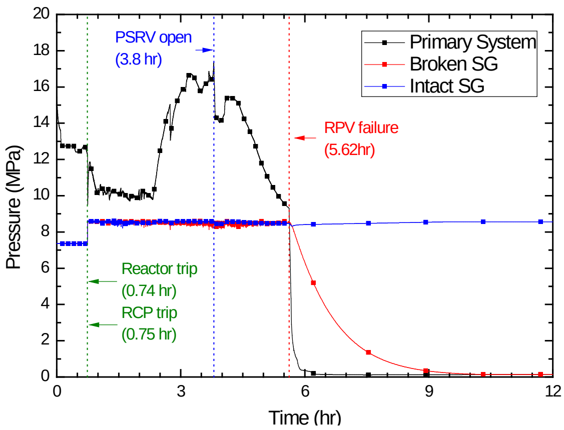

Fig. 3. RCS and SGs pressure of base case

Because of the difference between RCS and the broken SG, primary coolant was released into the secondary steam generator and contained radioactive nuclides can be released into the environment upon opening of MSSV installed in the steam generator. As shown as Fig. 5 - 6, total mass of Xenon and Cesium iodine are 19kg and 2kg at the beginning of the release, respectively. After cladding and UO2 melt, 282kg of Xenon and 24kg Cesium iodine are released to RCS. 203kg of Xenon was discharged to environment and 79kg of Xenon remained containment after RPV failure. In the case of Cesium iodine, 5kg of total 24kg was discharged to environment, 11kg of total 24kg remained in containment and 8kg of total 24kg deposited on RCS and SG.

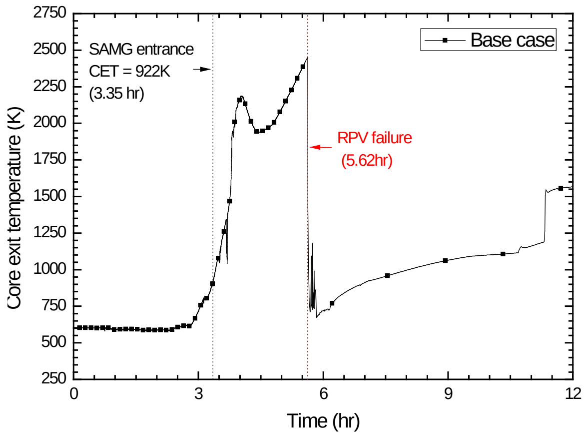

Fig. 4. CET of base case

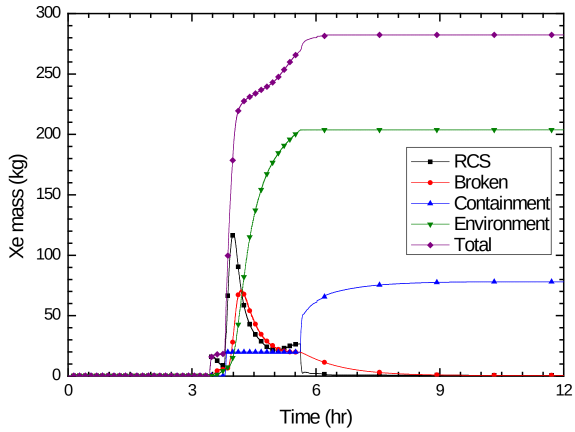

Fig. 5. Xe mass of base case

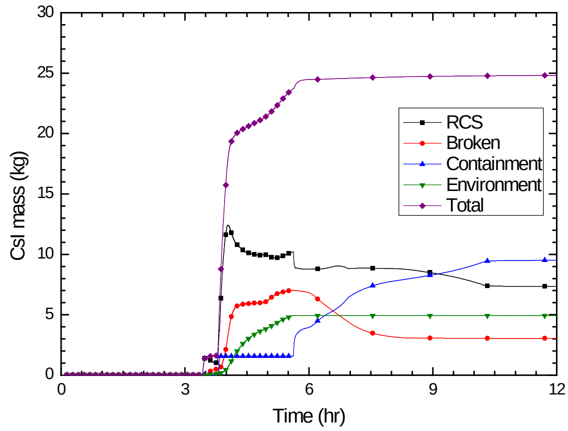

Fig. 6. CsI mass of SGTR

3.2 Effect of In-Vessel Mitigation Strategy

Three in-vessel mitigation strategies of injecting feed water into the intact SG with opening ADV (Mitigation 1), opening PORV of SDS (Mitigation 2), and injecting coolant into the RCS with HPSI pump (Mitigation 3) were simulated for 72 hours. It was assumed that mitigation strategies are applied immediately after the CET conditions reached the SAMG entrance condition of CET=922 K. Table III shows significant sequences during the accident progression with application of mitigation strategies. With the application of the Mitigation 1, owing to the recovery of heat removal by the SG, the RCS pressure could be reduced to the actuation point of the SIT and as a result no core degradation occurred. When applying Mitigation 2, the RPV failure was delayed by 2.85 hours because of some heat removal by the SIT injection but core degradation and resulting RPV failure was unavoidable in the long run. For the Mitigation 3, without effective reduction of the RCS pressure, long-term held of high pressure caused delay of coolant injection into the RCS by HPSI pump. RPV failure was delayed 2.74 hours.

Table III. Significant sequences of mitigation cases

Accident Sequences	Time (hr)		
	AFW +ADV	SDS	HPSI
SAMG entrance	3.35	3.35	3.35
Oxidation start	N/A	3.44	3.38
Gap release	N/A	3.48	3.43
Cladding melt	N/A	6.00	3.78
UO2 melt	N/A	6.07	3.80
Core dryout	N/A	3.44	3.84
Melt relocation	N/A	6.56	3.95
Broken SG dryout	N/A	25.31	5.44
SIT injection	3.82	3.50	8.39
SIT exhaust	27.91	4.43	8.57
HPSI pump start	N/A	N/A	5.29
RPV failure	N/A	8.47	8.36

Figures 7 and 8 show the released mass of typical fission products into the containment and environment, respectively. In case of Mitigation 1, since no core degradation and RPV failure were predicted, no fission products could be released into the environment and containment. Unlike the Mitigation 1, in case of the Mitigation 2, most of fission products was released into the containment but no fission product was released into the environment due to effective RCS depressurization. However, in case of Mitigation 3, 36 kg of xenon and 5 kg of cesium iodine were additionally released as compared with the results in the base case. It is observed that without proper RCS depressurization, delay of the RPV failure under high pressure state caused additional release.

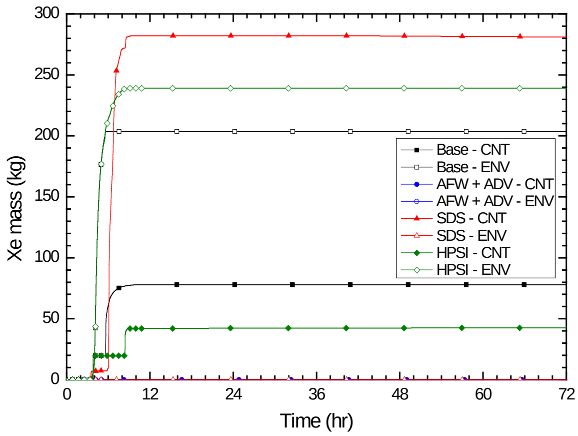

Fig. 7. Xe mass of mitigation cases

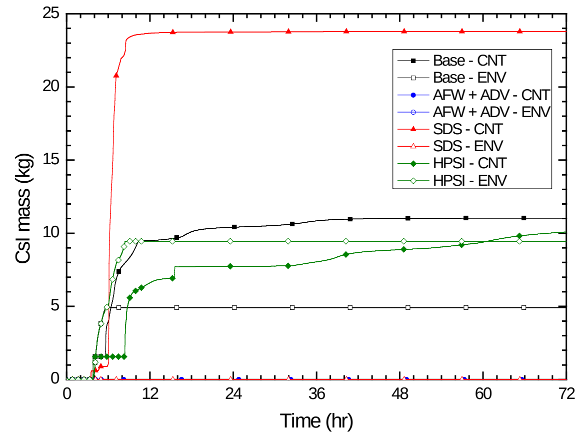

Fig. 8. CsI mass of mitigation cases

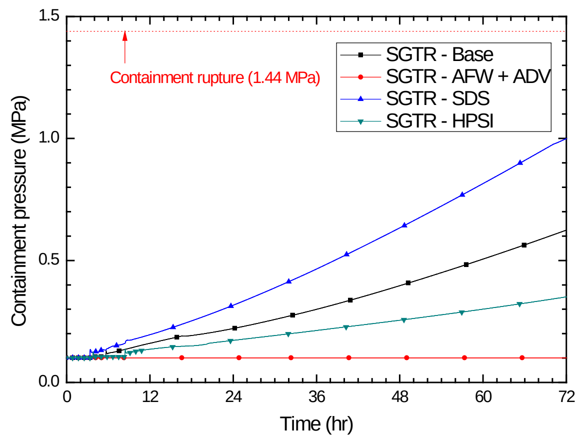

Fig. 9. Containment pressure of mitigation cases

In cases of Mitigations 2, some adverse effects are expected to occur in the thermal-hydraulic behavior of the containment building. As shown in Figs. 9 and 10, with the application of the Mitigation 2, containment pressure and temperature increased more than the respective result in the base case. This is related to the

RCS depressurization and subsequent high temperature steam release into the containment, which, in turn, elevates the containment pressure and temperature. As far as the Mitigation 3, adverse effects occurred in the hydrogen behavior of the containment. Fig. 11 shows hydrogen mole fraction in containment. The maximum mole fraction of hydrogen in the calculation of 72 hours was 0.075, 0.065 and 0.082 in the case of base, Mitigation 2 and Mitigation 3, respectively. The maximum Hydrogen mole fraction of Mitigation 3 was the highest due to relatively small amount of steam release.

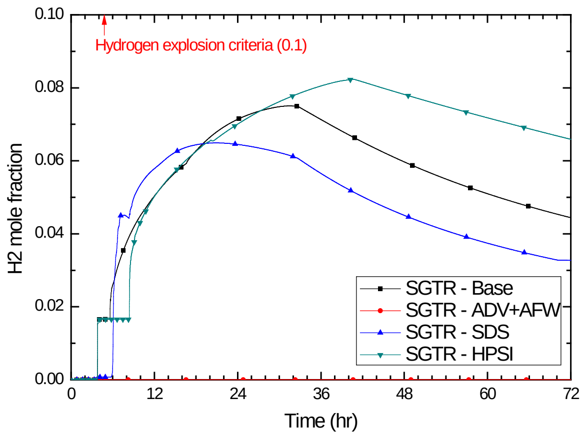

Fig. 9. Containment pressure of mitigation cases

4. Conclusions

Base case of SGTR accident and three mitigation cases were simulated using MELCOR code 1.8.6. For each mitigation cases, mitigation effect and adverse effect were investigated. Conclusions can be summarized as follows:

(1) RPV failure of SGTR base case occurred at 5.62 hours and fission product of RCS released to environment though MSSV which is located on broken steam generator.
(2) In Mitigation 1 case, no core degradation occurred and severe accident was terminated. Thus, recovery of feed water is a top priority of severe accident management in SGTR accident. In case of Mitigation 2, RPV failure was delayed up to 2.85 hours and fission product retained in containment building. Therefore, it could be a proper mitigation strategy, if none of safety feature such as AFW pump or HPSI pump is recovered.
(3) Opening PORV of SDS which is mitigation action of Mitigation 2 case can increase containment pressure and temperature. Accordingly, it needs suitable ex-vessel mitigation strategy for integrity of containment.
(4) It is observed that without proper RCS depressurization, delay of the RPV failure under high pressure state caused additional release in Mitigation 3 case. It means that RPV failure delay without proper depressurization of RCS may result in a worse consequence than that of no RPV failure delay case.

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