MELCOR Simulation of Effects of Cavity Flooding Strategy on the RPV Failure and Containment Leak for OPR1000

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1. Introduction

As one of the most promising severe accident management strategies, a number of reactors including Advanced Power Reactor 1400 MWe (APR1400) and Optimized Power Reactor 1000 MWe (OPR1000) consider an in-vessel retention (IVR) and/or an external reactor vessel cooling (ERVC) via cavity flooding strategy using the water inventory of fire protectin system addressed in the Final Safety Analysis Report (FSAR) [1, 2]. For the IVR, the ERVC strategy (i.e. flooding the reactor cavity) is to cool down the molten corium at the outer surface of the reactor pressure vessel (RPV) lower plenum to prevent or delay the RPV failure. However, while flooding the reactor cavity, if the molten materials cannot be retained inside the RPV during a postulated severe accident, the integrity of the containment may confront significant challenges such as fuel-coolant interaction (FCI), molten corium-concrete interaction (MCCI), and direct containment heating (DCH) [3].

For the current severe accident management guideline (SAMG) entry condition, once the core exit temperature (CET) reaches 923 K, the reactor operation is shifted from emergency operating procedure (EOP) to SAMG for the OPR1000. If the flooding of the cavity started at the time of SAMG entry condition, there will be no sufficient time to fill in the reactor cavity with water before the RPV failure. Therefore, the timing of the flooding has an important aspect for accident management by the operators. To increase the possibility of successful cavity flooding strategy, pre-flooding the reactor cavity may be considered before the CET reaches 923 K at EOP stage. However, if the RPV failure occurs with the presence of insufficient in the reactor cavity, high temperature corium might interact with the water and concrete in cavity while generating a large amount of gas and heat. This may lead to an pressurization of the containment and acceleration of fission product leak to the environment [4]. With aforementioned importance, in this paper, a sensitivity study was performed to investigate the effect of cavity flooding entry condition on delaying the RPV failure and containment leak time using severe accident code MELCOR, version 1.8.6.

2. Simulation descriptions

2.1 MELCOR input model of OPR 1000

MELCOR is the representative system code which enables to model the progression of severe accident in light water reactor nuclear power plant (NPP). This code was developed at Sandia National Laboratories supported by the U.S. Nuclear Regulatory Commission (NRC) [5].

The MELCOR nodalization of the containment and RPV included in the OPR1000 is presented Fig. 1. The containment input model consists of a cavity (control volume (CV) 810); an inner shell (CV 820); an annulus (CV810); and a dome (CV840). The RPV also consists of a downcomer (CV130); a core (CV170); the CET monitoring volume (CV 190); and a lower and an upper plenum (CV 150 and 260).

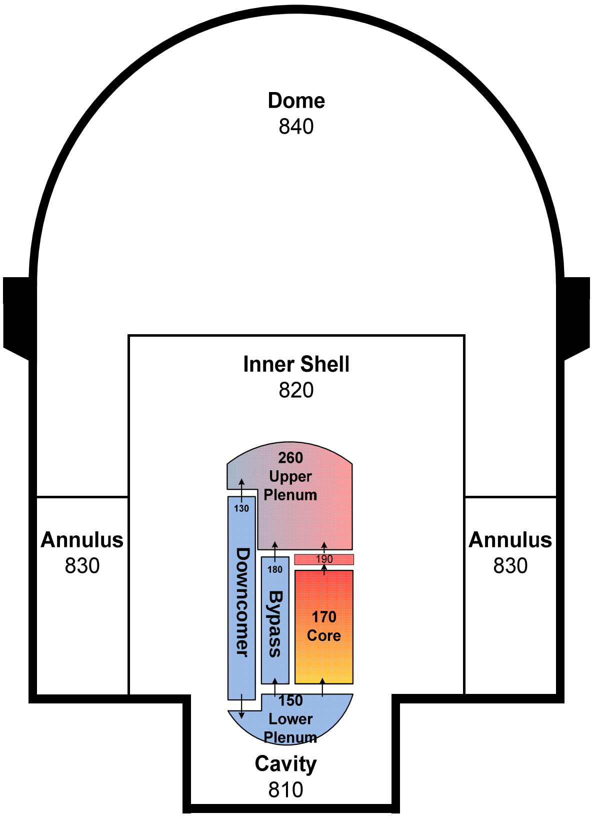

Fig. 1. MELCOR nodalization of Containment and Reactor Pressure Vessel on the OPR1000.

2.2 Simulation matrix

Table I shows the probability of transition from initiating events to severe accidents based on the probabilistic safety analysis (PSA) Level 1 for the OPR1000 [6]. Three cases with the high probability of transition to severe accident were chosen: small break loss of coolant accident without safety injection (SBLOCA without SI), station black out (SBO), and total loss of feed water (TLOFW). For the SBLOCA without SI, it is assumed that a 1.35-inch of the cold leg was broken. In case of SBO and TLOFW, loss of all off-site power and stopping all secondary feed water are assumed, respectively.

Table II summarizes a simulation matrix in this study. In order to investigate the effects of various cavity flooding entry conditions, three cases of embarking on timing of the cavity flooding were selected. First, as soon as the accident started, that is, when the CET reached 603.4 K (i.e. the initial accident temperature), the reactor cavity was flooded. Second, the SAMG entry conditions of the CET adopted by Combustion Engineering Owners Group (CEOG) and Westinghouse Owners Group (WOG) were used as 753 K and 923 K, respectively.

Table I: Probability of transition to severe accident for OPR 1000

Initiating event	Probability (%)
Small Break Loss of Coolant Accident without Safety Injection	22.4
Station Black Out	14.4
Total Koss of Feed Water	13.8
Steam Generator Tube Rupture	13.8
Large Break Loss of Coolant Accident without Safety Injection	12.7
Medium Break Loss of Coolant Accident without Safety Injection	7.7

Table II: Summary of the simulation matrix

Event	Mitigation	CET (Entry condition)
SBLOCA	OFF	N/A
	Cavity Flooding	603.4 (Accident Start), 758, and 923 K
SBO	OFF	N/A
	Cavity Flooding	603.4 (Accident Start), 758, and 923 K
TLOFW	OFF	N/A
	Cavity Flooding	603.4 (Accident Start), 758, and 923 K

3. Results and Discussion

3.1 Steady State Analysis

To confirm the suitability of MELCOR simulation results, the MELCOR steady state calculation was performed to compare with the various designed parameters reported in the FSAR [2]. Table III shows the operating conditions described in the FSAR and steady state parameters of the OPR1000 input model of MELCOR. It is shown that the MELCOR calculation results are in good agreement with the nominal FSAR values.

Table III: Comparison between Design value and steady state conditions of OPR1000

Parameter	FSAR	MELCOR
Core thermal power (MWt)	2815	2815
RCS pressure (MPa)	15.5	15.5
Core inlet temperature (K)	568.8	573.2
Core outlet temperature (K)	600.3	603.4
Primary flow rate (kg/sec)	15,305.5	15,498
SG pressure (MPa)	7.37	7.37
Steam flow per SG (kg/sec)	800.0	808.5

3.2 Base Cases

Table IV shows timeline of major sequences for base case. Each of the MELCOR simulations begins at 0 second. For all three base cases, when the cladding surface temperature reached nearby 950 K, the fuel rod cladding oxidizes and the cladding temperature increases rapidly because of decay and exothermic oxidation heat. As the fuel rod temperature dramatically increases, the fuel rod is melted and relocated to the lower plenum. After relocation to the lower plenum, for the SBLOCA without SI, SITs were initiated because the primary system pressure was sufficiently lowered below the set point of the SIT injection. However, in case of SBO and TLOFW, SITs were not activated because the inner pressure of the RPV maintained higher than the SIT injection set pressure. The RPV failure occurred by the lower head penetration for the SBLOCA without SI and SBO and by creep rupture for the TLOFW. The RPV failure times were estimated at 5.82, 3.78, and 2.30 hours for SBLOCA without SI, SBO, and TLOFW, respectively. It is further postulated that after the RPV failure, a corium is injected into the reactor cavity and interacts with the concrete, which subsequently releases a large amount of heat and non-condensable gas. Containment is pressurized and the containment integrity can eventually be threatened by these multiple phenomena.

Table IV: Timeline of major sequences of base case

Accident Sequences	Time (hr)		
	SBLOCA without SI	SBO	TLOFW
Accident start	0.00	0.00	0.00
Reactor trip	0.04	0.00	0.01
RCP trip	0.06	0.00	0.37
Oxidation	2.35	2.29	1.08
Cladding melt	2.64	2.65	1.36
UO_2 melt	2.67	2.67	1.38
Relocation to lower plenum	2.89	2.83	1.56
SIT injection	3.64	-	-
RPV failure	5.82	3.78	2.30
Containment leak	30.93	39.54	34.60

3.3 Assessment of Timing the Reactor Cavity Flooding

The effect of cavity flooding timing on the RPV failure was evaluated in terms of the RPV failure delay. Table V shows operator's available action time between cavity flooding entry time and RPV failure time of the base case. The mitigation is implemented immediately as soon as the CET reaches 603.4, 753, and 923 K using the water inventory of fire protection system addressed in the FSAR. To submerge lower plenum of the RPV, it takes time of about 1.72 hrs. However, if the flooding started when the CET reaches 923 K for SBO and TLOFW scenarios, insufficient time to immerse the lower plenum of RPV is predicted. Thus, it is of importance to complete the cavity flooding for ex-vessel cooling before the RPV failure.

Table V: Available Operator's Action Time between Cavity Flooding Entry Time and RPV failure Time of Base case

Cavity flooding entry condition when CET =	Available operator's action time (hr)		
	SBLOCA without SI	SBO	TLOFW
603.4 K	5.82	3.78	2.30
753 K	3.60	1.65	1.33
923 K	3.44	1.53	1.22

Table VI shows the delayed RPV failure time. For all three base cases, during the cavity flooding, water reached at the lower plenum surface of the RPV before the RPV failure. For this reason, the MELCOR simulation predicted delayed RPV failure time ranged from 0.25 to 2.74 hours. In addition, regardless of accident scenarios, with the earlier cavity flooding timing, the more delayed RPV failure was predicted. Unlike the SBO and TLOFW scenarios, for the SBLOCA, while filling the water in the reactor cavity, SITs were activated because the RCS pressure decreased below 4.3 MPa (i.e. set point of the SIT injection). This contributed to provide more cooling to the corium in the RPV and delayed the RPV failure compared with the others cases.

Table VI: Delayed RPV failure time of cases with timing of the cavity flooding

Cavity flooding entry condition when CET =	Delayed RPV failure time (hr)		
	SBLOCA without SI	SBO	TLOFW
603.4 K	2.74	1.43	1.17
753 K	2.06	0.86	0.81
923 K	0.25	0.55	0.75

Figures 2, 3, and 4 represent the containment pressure for SBLOCA, SBO, and TLOFW, respectively. For all three cases, after the RPV failure, containment pressure gradually increased for the following reasons. First, molten corium interacting with the coolant generated a large amount of gas until the water was exhausted in reactor cavity. Second, after the cavity water dried out, containment temperature also increased dramatically owing to releasing the heat from the MCCI. This evaporated the water in the containment and produced a large amount of the steam. Therefore, containment was pressurized and overheated by the FCI and MCCI.

For the SBLOCA, in case of the cavity flooding, containment leak time decreased by maximum 3 hours compared to the base case. On the other hand, for the SBO and TLOFW, the cavity flooding delayed containment leak time about maximum 1.4 and 2.7 hours, respectively. The injected SITs into the corium was likely to produce more steam. As a result, containment pressure in the SBLOCA case increased more dramatically than the SBO and TLOFW cases. Before the cavity water dried out, containment pressure was reached to the limit of the containment leak. Therefore, for the SBLOCA, premature containment leak can be predicted. For the SBO and TLOFW, when the flooding the cavity, containment leak time is delayed from minimum 0.1 hours to maximum 2.7 hours.

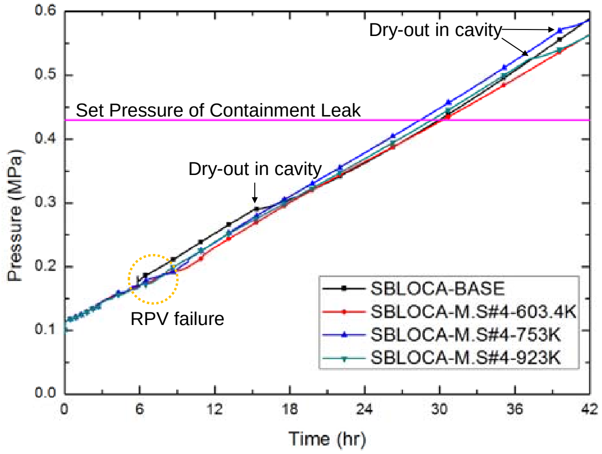

Fig. 2. Containment pressure of SBLOCA cases

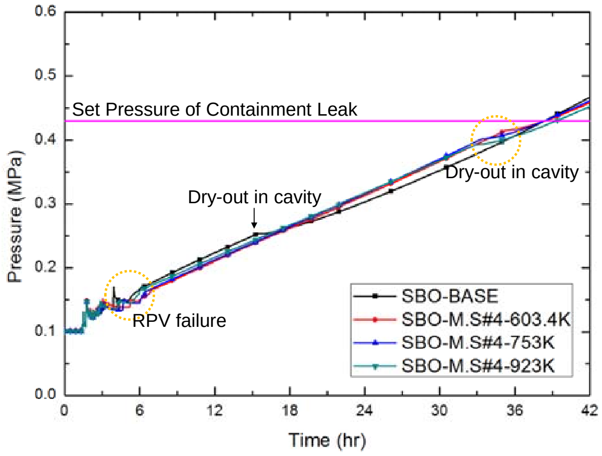

Fig. 3. Containment pressure of SBO cases

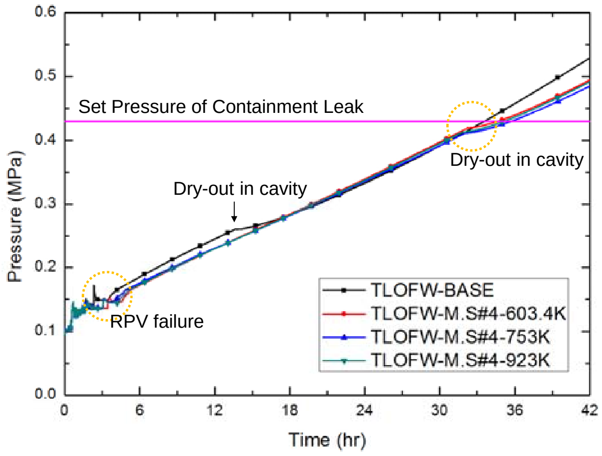

Fig. 4. Containment pressure of TLOFW cases

4. Conclusion

In this work, using severe accident code MELCOR, version 1.8.6, the effect of cavity flooding timing on the RPV failure and containment leak was calculated regarding the delayed RPV failure and containment leak time. The main conclusions from this study are summarized as follow.

(1). The MELCOR simulation results confirmed that the timing of the cavity flooding influenced the RPV failure time and the containment leak time.

(2). For all three base cases, it was predicted that the RPV failure time was delayed as the cavity flooding timing becomes earlier. Especially, for the SBLOCA, when the cavity flooding started at CET =603.4 K, the RPV failure time delay was evaluated approximately 3 hours.

(3). In terms of containment leak time, the cavity flooding affected the containment leak time considerably. The containment leak time with SBLOCA case was fastened compared to the base case. However, for the SBO and TLOFW, in case of the cavity flooding, containment leak time was somewhat delayed.

Acknowledgements

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1403002)

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