Severe Accident Analysis in Mid Loop Operation at OPR1000 Using MELCOR

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1. Introduction

As at least six units are located on a site of the nuclear power plants, people are worried about accidents occurring in multi-units at the same time after the Fukushima accident in 2011. To assess the safety of the nuclear power plant systematically, a probabilistic safety assessment (PSA) has been developed and the importance of multi-unit PSA has been increased. Among nuclear power plants in a site, some units are often in low power and shutdown (LPSD) operation, due to overhaul. Therefore, it is realistic to consider LPSD operation units along with the full power units when performing multi-unit PSA.

The plant operational states (POS) are defined by considering the configuration of the nuclear power plant in LPSD operation. The POS5 is generally called mid loop operation because the water level of the reactor coolant system (RCS) is maintained at the center level of the hot leg. In mid loop operation, even a small reduction of coolant may lead to a loss of shutdown cooling system (SCS), causing the coolant to boil and core damage. The core damage frequency (CDF) in POS5 is 5.44E-7 /yr and has a significant contribution of 19.7% to the total CDF in LPSD [1].

Thermal-hydraulic analyses in POS5 for LPSD PSA have been conducted using MARS and RELAP for OPR1000 [1,2,3]. However, the previous studies focused only on core damage. To carry out the LPSD PSA level 2&3, it is necessary to analyze the accident progress and phenomena after the core damage. In this study, MELCOR calculation was performed for the mid loop operation mode. The accident progression and results for the full power operation were also analyzed for comparison with the mid loop operation calculations.

2. Methods

2.1 MELCOR modeling

The OPR1000 is a pressurized water reactor in Korea, which produces 2815 MWth, and consists of two steam generators (SG). Each SG is connected with two cold legs and one hot leg [4]. Figure 1 shows the nodalization of the RCS in full power operation [5]. Based on this nodalization scheme, new flow junctions are added for the mid loop operation considering the coolant flow from the SCS. The flow rate of it is 315.45 kg/sec [4]. For the steady-state calculation, this flow rate is provided to the cold legs and the discharge rate from the hot legs is determined by maintaining the water level at both hot leg and cold leg.

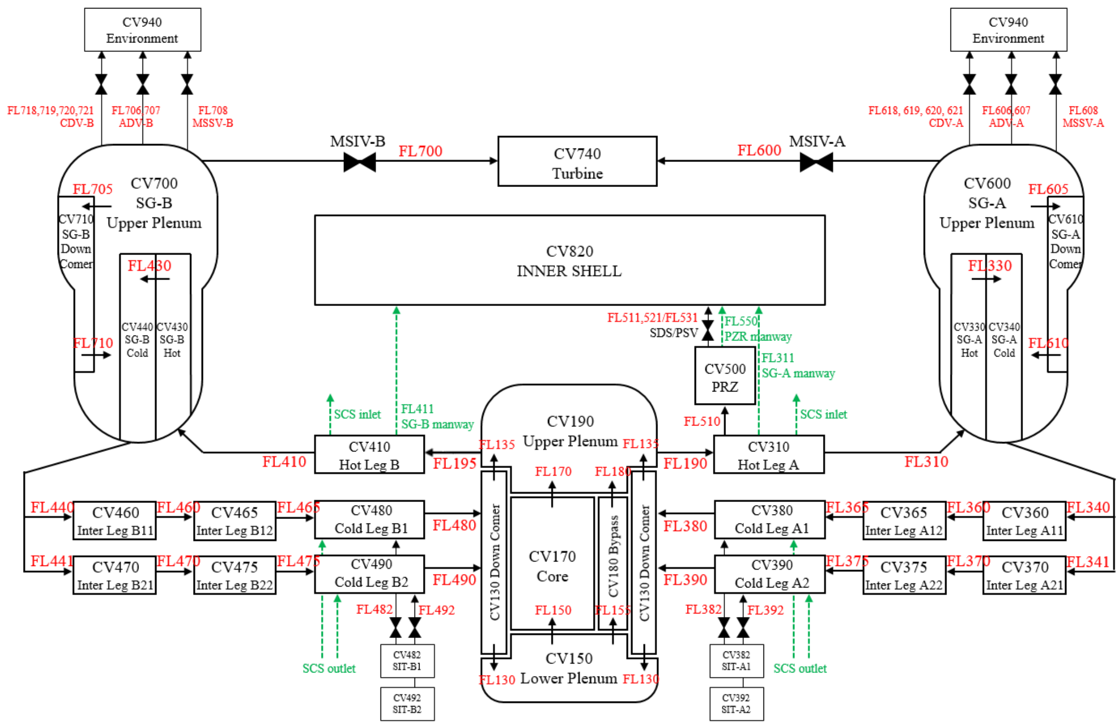

Fig. 1. The RCS nordalization of OPR1000 MELCOR model

Table I: Major parameters calculated from MELCOR and reference values of steady-state [1,2,4,6,7]

Parameter	Mid loop operation			Full power operation		
	Reference value	MELCOR	Error [%]	Reference value	MELCOR	Error [%]
Decay heat/Core heat output [MW]	12.183	-	Input value	2185	-	Input value
PZR, SG manway diameter [m]	0.4064	-	Input value	-	-	-
RCS pressure [kPa(a)]	101.33	101.37	0.04	15513	15504	-0.06
RPV[a)] outlet coolant temperature [K]	324.85	325.19	0.10	600.45	602.39	0.32
RPV[a)] inlet coolant temperature [K]	316.05	316.03	-0.01	568.95	572.12	0.56
RCS coolant mass [ton]	-	92.72	Calculated in MELCOR	-	212.50	Calculated in MELCOR
SIT volume [m^3]	-	-	-	52.6	-	Input value
RPV[a)] inlet coolant flow rate [kg/sec]	315.45	-	Input value	15311	15609	1.94
Containment failure pressure [kPa(a)]	808.7[b)]	-	Input value	1328.6[c)]	-	Input value

a) Reactor pressure vessel
b) Based on the containment configuration for the mid loop operation
c) Based on the containment configuration for the full power operation

Based on the average time of 79.5 hours from shutdown to just before POS5 entry, the decay heat of 12.183 MW is used as an initial power [1]. The manways of SG-A, B and PZR have a diameter of 0.4064 m [2]. To simplify the model, the SG inlet and outlet volumes are not modeled separately and they are included in each hot leg and inter leg. Therefore, the manway on the SG is modeled as a flow path connecting each hot leg and inner shell of containment. Since the manways are always open, the pressure of the RCS maintains atmospheric pressure. The coolant temperature at the outlet and inlet of RPV is assumed to the inlet and outlet temperature of the SCS heat exchanger [4]. The most vulnerable part in the mid loop operation for the containment integrity is evaluated as the equipment hatch, and its failure pressure is 808.7 kPa(a). The damaged area of the containment is assumed to 1 ft^2 [6]. Table I shows a comparison of the major parameters of MELCOR calculation and reference values of the mid loop and full power operation model. It is confirmed that both models simulate the steady-state properly.

2.2 Reference accident scenario

According to the results of the analysis of the CDF for each initiating event in LPSD level 1 PSA, the CDF of station blackout (SBO) accounts for 36.5%, the largest among the LPSD CDF [1]. If an SBO occurs during a mid loop operation, the SCS, which is removing the residual heat, stops working and the core can be damaged. As a reference accident scenario, an SBO that fails to recover power is selected, and no accident mitigation measures are taken by the operator. When an SBO occurs in mid loop operation, coolant cannot be supplied from the SIT, since the SIT is isolated. As the RCS is open, the coolant in the RCS easily evaporates into the containment. It is assumed that mitigation measures of the operator are not taken and gravity feed is assumed unavailable.

For the comparison purpose, the SBO sequence at full power operation was also analyzed. When SBO occurs during full power operation, the reactor coolant pumps and the main feed water pumps stop working. Due to the decay heat, the pressure of RCS rises, and the pressurizer safety valve (PSV) opens when the RCS pressure is reached to the set-point. Since the recovery of power fails, the safety injection pumps can not work, and only the SIT supplies coolant to the RCS.

MLO-SBO and FPO-SBO were named for the accident cases when an SBO occurs in each of operation modes of the mid loop and full power operation. The accident analysis was conducted for three days after the accident occurred.

3. Results

3.1 Accident progression analysis

Table II: Accident progression when an SBO occurred

Event	MLO-SBO [hr]	FPO-SBO [hr]
Station blackout	0.00	0.00
Boiling starts in the core	0.23	0.86
PSV first open	-	1.43
SAMG entry[a)]	4.61	2.27
Oxidation starts in the core	4.69	2.34
Gap release	4.75	2.38
Core dry out	6.16	2.65
RPV failure	8.80	4.22
SIT injection	-	4.24
SIT end	-	4.39
Reactor cavity dry out	22.16	45.21
Containment failure	-	53.85

a) Severe accident management guidance (SAMG) entry condition is when the core exit temperature exceeds 650 ℃ [8]

Table III: Results of accident analysis

Parameter	MLO-SBO	FPO-SBO
H_2 mass generated in the core[a)] [kg]	374.5	496.5
H_2 mass generated in the cavity[a)] [kg]	734.1	539.6
Zr mass ejected to reactor cavity [ton]	16.7	13.6
ZrO_2 mass ejected to reactor cavity [ton]	9.2	14.7
Axial eroded depth of cavity concrete[a)] [m]	1.3	1.6
Cs mass in RCS[b)] [kg]	23.5	74.4
Cs mass in containment[b)] [kg]	88.6	37.4
Peak containment pressure [kPa(a)]	530.5	1328.6[c)]
Release fraction of Cs to environment[a)] [-]	-	0.050

a) After three days of the accident occurred
b) Before containment failure
c) Containment failure pressure

Tables II and III shows the timing of the major events and the important accident progression parameters in both accident scenarios. In MLO-SBO, the SCS was unavailable at 0.00 hr. Then, the core water temperature rose and reached a saturation temperature at 0.23 hr (828 sec), and water in the core started to boil. As shown in Figure 2, the active core began to be uncovered at 3.61 hr, and the core exit temperature reached the SAMG entry condition at 4.61 hr (see Figure 3). After the fuel cladding was damaged at 4.75 hr, and the fission products in the fuel rods leaked into the RCS. Then, the core was fully exposed at 6.16 hr. The damaged fuel was relocated to the bottom of the RPV, heating the bottom of it, and the RPV failed at 8.80 hr eventually (see Figure 2).

In MLO-SBO, the hydrogen generation started in the core at 4.69 hr. About 31% of Zr reacted and produced 337 kg of hydrogen and 4% of stainless steel produced 35.8 kg. After the RPV was failed, the molten corium relocated to the bottom of RPV was released to the reactor cavity. The molten corium and concrete interaction generated non-condensable gases and hydrogen. The coolant in the reactor cavity evaporated and reacted with the metal in the molten corium to generate hydrogen. Among the metals of the molten corium, Zr reacts with vapor in the early phase and Fe reacts later [9]. About at 48.33 hr, the Fe in condensed phase was completely oxidized (see Figure 4).

Since FPO-SBO had a greater initial decay heat compared to the RCS water inventory, the SAMG entry condition and RPV failure of FPO-SBO occurred earlier than MLO-SBO. The time of the reactor cavity dry out at FPO-SBO was delayed about 23 hr than that of MLO-SBO due to the SIT injection after the RPV failure. The amount of coolant in the RCS of FPO-SBO was about 120 tons greater than that of MLO-SBO, and more steam was generated in the core. As a result, about 122 kg of more hydrogen was produced from the core in FPO-SBO. After RPV failed, more Zr was released into the reactor cavity in MLO-SBO than FPO-SBO, resulting in about 194 kg of a larger amount of hydrogen generation in the reactor cavity.

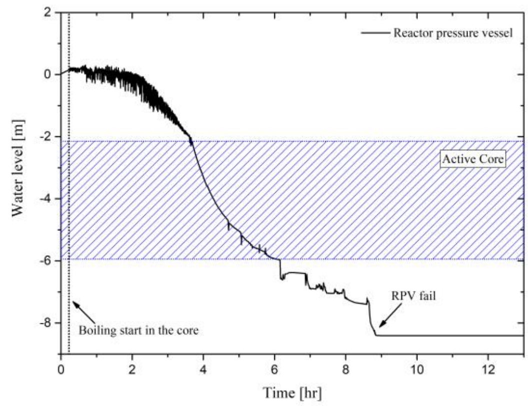

Fig. 2. The water level of the reactor pressure vessel (MLO-SBO)

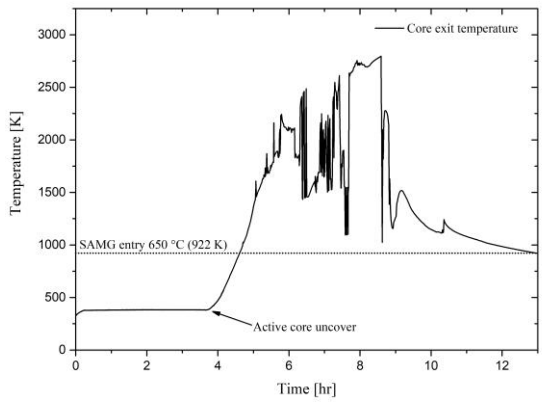

Fig. 3. Maximum core exit temperature (MLO-SBO)

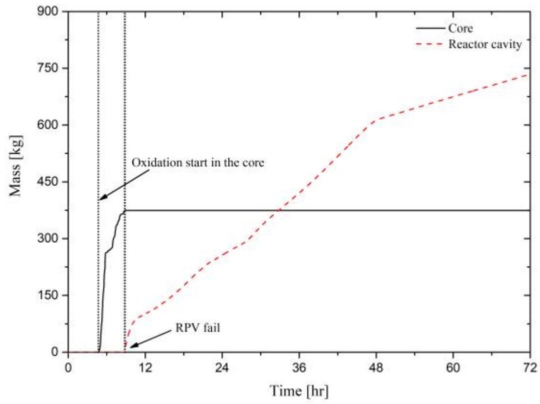

Fig. 4. Hydrogen mass generated in the core and reactor cavity (MLO-SBO)

3.2 Analysis of Cs behavior

In MLO-SBO, the containment maintained its integrity, so that the fission product was not released into the environment. This section evaluates the mass distribution of Cs in the containment and RCS. Before the failure of containment, the mass of Cs in the containment was estimated to be 88.64 kg and 37.35 kg respectively, at each accident scenario. The mass of Cs in the RCS was estimated to be 23.49 kg and 74.38 kg, each (see Figure 5). The mass of Cs in the containment was much higher in MLO-SBO than in FPO-SBO. This is because most of Cs in FPO-SBO was chemisorbed on the surface of the RCS. The mass chemisorption coefficient calculated in MELCOR is temperature dependent [10]. Due to the high residual heat of FPO-SBO, the surface of the RCS was maintained at a higher temperature than MLO-SBO. As a result, the chemisorption of Cs occurred significantly in FPO-SBO. Before the failure of containment, the mass of chemisorbed Cs was 5.95 kg and 59.15 kg respectably, each (see Figure 6).

The amount of fission products present in the containment contributes significantly to the mass released into the environment when the containment failed. If the containment failed in an accident during mid loop operation, more Cs will be released into the environment in this accident than FPO-SBO.

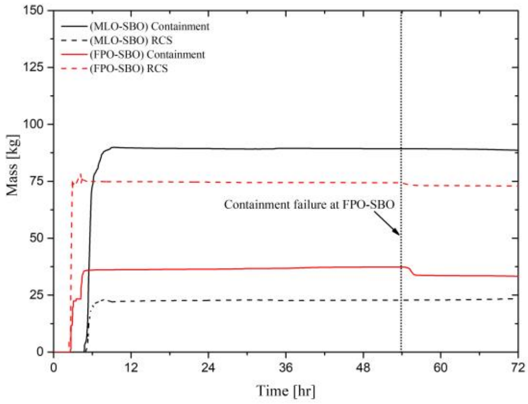

Fig. 5. Total Cs mass in the containment and RCS (MLO-SBO, FPO-SBO)

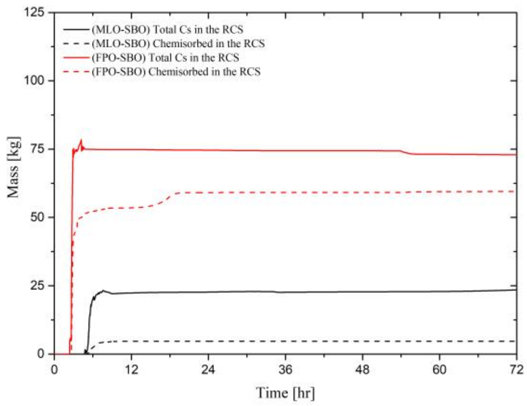

Fig. 6. Cs mass chemisorbed in the RCS (MLO-SBO, FPO-SBO)

4. Conclusions

In this study, the MELCOR model in the mid loop operation was developed, and the severe accident analysis was performed in the case of an SBO without accident mitigation action. A similar scenario at the full power operation was also analyzed for the comparison.

In the MLO-SBO, the core exit temperature reached the SAMG entry condition at 4.61 hr and the RPV was failed at 8.80 hr. The accident progression until the RPV failure was delayed in MLO-SBO than FPO-SBO since the decay heat per RCS water inventory of MLO-SBO was seven times smaller than FPO-SBO. Though the containment pressure rose to 530.5 kPa(a), it was not reached to containment failure pressure and containment kept its integrity. As a result, no fission products were released to the environment, ignoring the leakage paths. The amount of Cs in the containment of MLO-SBO was two times higher than FPO-SBO. Therefore, if the containment is failed during mid loop operation, more Cs can be released into the environment than an accident in full power operation.

In this study, an SBO in mid loop operation was analyzed. For future work, the severe accident analysis is needed for other POS and initiating events.

Acknowledgements

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