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Thermal-Hydraulic Modeling and Sensitivity Analysis of Multiple Steam Generator Tube Rupture Event in Shin-Kori Units 1&2

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1. Introduction

After the Fukushima nuclear accident, beyond design conditions have played an important role for developing the reactor coolant system (RCS) cooldown strategy and recovery action. Additional failures of the safety components are also considered in terms of sufficient safety margin with application of proper emergency operating procedures [1].

The multiple steam generator tube rupture (MSGTR) as one of the prescribed multiple failure accidents is an event in which multiple U-tubes in one steam generator are ruptured at the same time. This event damages the barrier between the primary coolant system and main steam system, leading to an atmospheric release of the radioactive inventory bypassing the containment through the secondary system.

The analysis results could be affected by several factors such as rupture locations in U-tube, the number of ruptured tube, selection of the affected SG, and a discharge coefficient at the break point for the thermal-hydraulic analysis [2].

In this investigation, the sensitivity analysis was applied to identify the effects of two most important parameters which are rupture locations and the number of ruptured tube on the analysis results of the MSGTR event. Key safety parameters such as system pressures, leak flow rate to the secondary side, SG level, and the opening time of main steam safety valves (MSSVs) were analyzed and compared for each case. The target plants are Shin-Kori Units 1&2.

2. Modeling and Analysis

2.1 Analysis method

The RELAP5 Mod 3.3 code is used to analyze the thermal hydrodynamic behavior of the MSGTR event in transient period [3]. The nodalization diagram of the target system is shown in Fig. 1.

2.2 Analysis conditions

The steady state calculation was performed in order to obtain appropriate initial conditions prior to the initiation of the MSGTR event. The comparison of plant design values and steady state simulation results is shown in Table 1. The calculation error is within 0.6 percent. It indicates that the major parameters of the primary and secondary system correspond closely to the real plant conditions.

The MSGTR event is summarized as follows. Once the event is initiated, the reactor coolant start to be leaked to the secondary system. The reactor trip signal is generated by the hot-leg saturation temperature or low pressurizer pressure signal. The leaked reactor coolant mixed with the secondary coolant could be sent to the condenser or released to atmosphere through MSSVs. Since the releasing gas contains radioactive materials, the MSSVs lift time is one of important factors to protect people and environment during the MSGTR event.

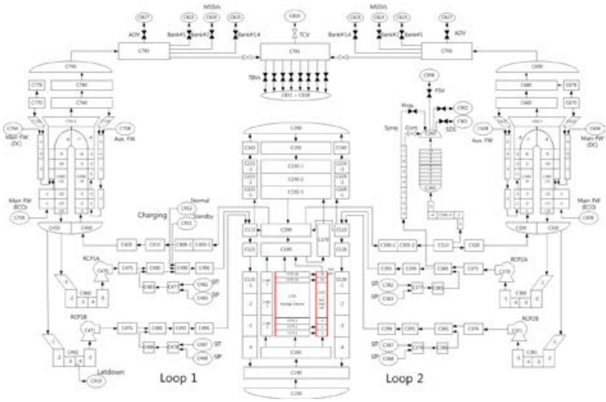

Fig. 1. Nodalization of Shin-Kori Units 1&2

Table 1. Initial conditions for MSGTR

Parameter	Design value	Steady state value
Core power (Wt)	2.815×10^6	2.815×10^6
Pressurizer pressure (MPa)	15.5132	15.5201
Pressurizer level (%)	52.60	52.51
Hot-leg temperature (°C)	327.23	327.20
Cold-leg temperature (°C)	295.83	295.89
RCS flow rate (kg/s)	15,308.7	15,298.1
Steam dome pressure (MPa)	7.5429	7.5150
Total FW flow per SG (kg/s)	802.9	798.3
SG level (%WR)	79	79
Circulation ratio	3.7	3.7

Table 2. Description of analysis cases

Case no.	No. of ruptured tubes	Rupture location
Case 1 (5 tubes rupturing case)	5	Hot-leg side
	5	Tube top side
	5	Cold-leg side
Case 2 (Hot-leg side ruptured case)	1	Hot-leg side
	3	Hot-leg side
	5	Hot-leg side

The sensitivity study is conducted depending on two important parameters, rupture locations and the number of ruptured tube, to find out their effects on the main thermal hydrodynamic parameters. Table 2 summarizes all cases for the sensitivity analysis.

2.3 Results of sensitivity analysis

Figs. 2 to 5 present the comparison results of main parameters of thermal hydrodynamic behaviors for Case 1 which has different rupture locations such as the hot-leg, tube top, and cold-leg side. In this case, SG 1 is assumed as the affected steam generator.

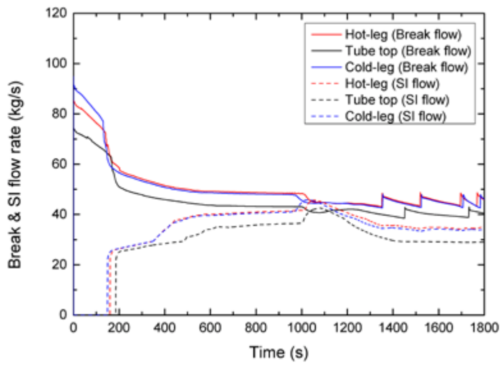

Fig. 2. Break and SI flow rates (Case 1)

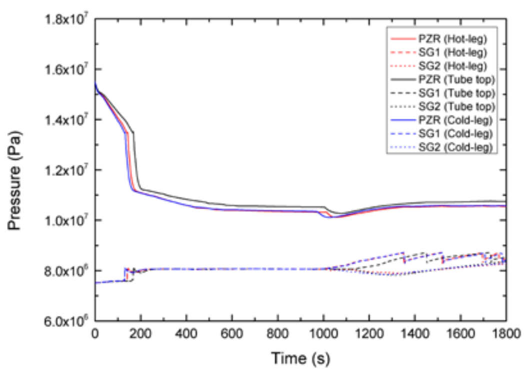

Fig. 3. Primary and secondary system pressures (Case 1)

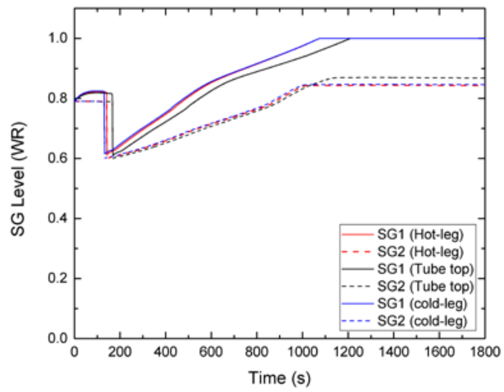

Fig. 4. SG levels (Case 1)

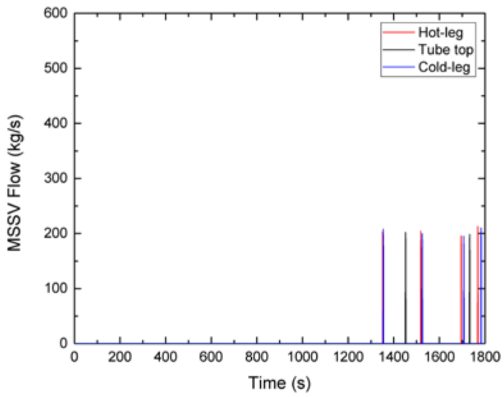

Fig. 5. MSSV flows (Case 1)

Variations of the break and safety injection (SI) flow rates for Case 1 are shown in Fig. 2. Although the cold-leg side ruptured case has the largest initial leak flow, 94.9 kg/s, the average leak flow rate of 48.3 kg/s for the hot-leg side ruptured case is the most. After the reactor trip, RCS pressure is rapidly decreased and reaches a safety injection set point as shown in Fig. 3. After the safety injection is initiated, the break flow rate and primary pressure stay about the same.

The levels of the SGs are depicted in Fig. 4. The SG level temporarily decreased due to the reactor and turbine trip and then increase again after the high pressure safety injection (HPSI) actuation. The level of the affected SG increase faster than the other because of the leak flow from the primary side, and then the main steam insolation signal (MSIS) is generated by the high steam generator level signal.

Fig. 5 presents the effects of rupture locations on the MSSV opening time. All cases have the similar opening times, but the shortest one occurs in the hot-leg side ruptured case. The largest accumulated discharge mass through MSSVs also appears to be the case of hot-leg side.

Table 3. Sequence of the events for Case 1

Event	Time, sec		
	Hot-leg	Tube top	Cold-leg
Tube(s) break	0	0	0
Reactor trip (by hot-leg saturation temperature signal)	140	166	130
HPSI actuation	160	186	150
MSIS generation (by high SG level signal)	996	1,123	993
MSSV open	1,351	1,451	1,354

The result of sensitivity analysis for different rupture locations shows that each case reports similar trends in the key safety parameters. Which means that the rupture location has a minor influence on the result. Table 3 summarizes the event sequence of Case 1. There are no significant difference between the hot-leg and cold-leg side ruptured case, but the former has the shorter MSSVs opening time and the larger accumulated discharge mass through MSSVs.

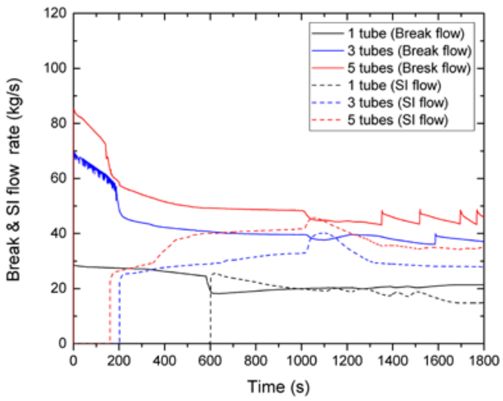

Fig. 6. Break and SI flow rates (Case 2)

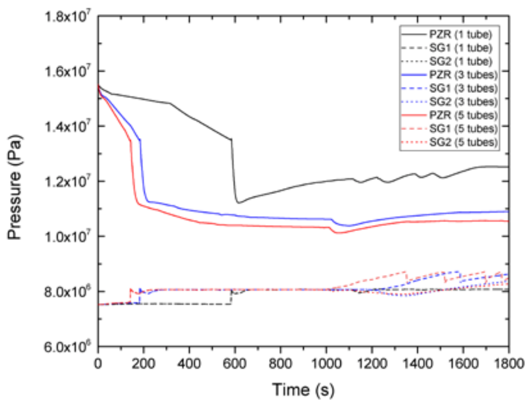

Fig. 7. Primary and secondary system pressures (Case 2)

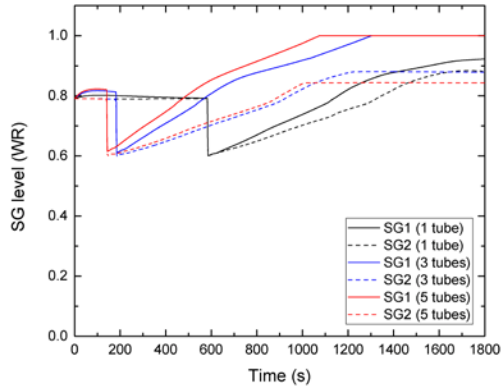

Fig. 8. SG levels (Case 2)

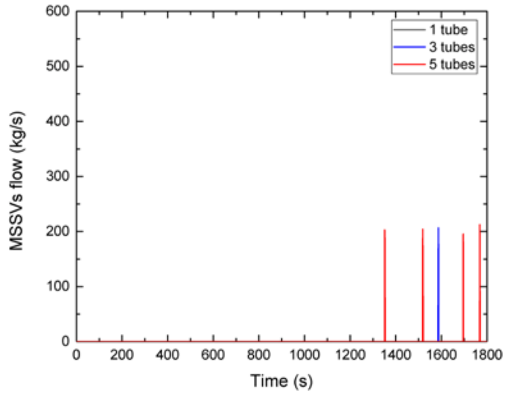

Fig. 9. MSSV flows (Case 2)

Table 4. Sequence of the events for Case 2

Event	Time, sec		
	1 tube	3 tubes	5 tubes
Tube(s) break	0	0	0
Reactor trip (by hot-leg saturation temperature signal)	582	182	140
HPSI actuation	601	202	160
MSIS generation (by high SG level signal)	2,722	1,210	996
MSSV open	-	1,586	1,351

Figs. 6 to 9 present the comparison results of Case 2 which is the hot-leg side ruptured case having a different number of the break tubes. The SG 1 is also assumed as the affected steam generator.

Fig. 6 presents the break and SI flows. The break flows decrease as reduction of the pressure difference between primary and secondary systems. RCS is rapidly depressurized right after the reactor trip and reaches a safety injection set point as shown in Fig. 7. After the

HPSI actuation, the break flow rate and primary pressure stay about the same or slightly increases again in the 1 tube rupturing case. The 5 tubes rupturing case leads to the largest leak rate, 85 kg/s with compared other two cases.

The levels of the SGs are temporarily decreased due to the reactor and turbine trip and then increase again as shown in Fig. 8. The level of the affected SG increase faster than the intact SG because of the leak flow through the break tubes and the MSIS is generated at the high steam generator level.

The effects of a number of ruptured tubes on the MSSV opening time are depicted in Fig. 9. The first MSSV opening times of the 3 and 5 tubes rupturing cases are 1,586 seconds and 1,351 seconds, respectively. And then the MSSVs repeat open and close. On the other hands, the MSSVs are not lifted in the 1 tube rupturing case. The 5 tubes rupturing case has the shortest MSSV opening time and the largest accumulated discharge mass than others.

Table 4 summarizes the event sequence of Case 2. The analysis results indicate that the 5 tubes rupturing case gives the most conservative results to the MSGTR event in the hot-leg side ruptured case.

3. Conclusions

This study investigated the effects of two important parameters, the number of the ruptured tube and the rupture location, on the result of the MSGTR event. The RELAP5 Mod 3.3 code was used to obtain the thermal hydrodynamic behaviors of the event.

The results of the sensitivity analysis indicated that the main parameters such as the break flow rate, SG level, and MSSVs lift time are very sensitive to the number of the ruptured tubes. The rupture locations, the other hands, were not significant.

Overall, the case of the five tubes rupture at the hot-leg side presented the largest accumulated discharge mass through MSSVs and the shorter MSSVs opening time, which means that it gave the most conservative results to the main thermal hydrodynamic parameters of the MSGTR event.

REFERENCES

[1] Korea Hydro and Nuclear Power Co. Ltd., “Development of Design Extension Conditions Analysis and Management Technology for Prevention of Severe Accident Report”, September, 2017.

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[3] RELAP5/MOD3.3 Code Manual, ISL, 2016.