Prediction of Golden Time for Recovering the Safety Injection System in Severe LOCA Circumstances

Kwae Hwan Yoo, Dong Young Kim, Geon Pil Choi, Ju Hyun Back, and Man Gyun Na*
Department of Nuclear Engineering, Chosun University, 309 Pilmun-daero, Dong-gu, Gwangju, Korea
**Corresponding author: magyna@chosun.ac.kr*

1. Introduction

Nuclear power plants are designed in consideration of design basis accidents (DBAs). DBAs such as loss-of-coolant accident (LOCA) in nuclear power plant (NPP) may lead to serious accidents that exceed the DBAs due to failure of safety systems. Also, there is a case in which a serious accident occurs due to natural disasters and operator mistakes. The perfect example of that was the nuclear accident in Fukushima. In the case of the LOCA and station blackout (SBO), to recover the accident, the reactor must safely be cold shutdown. If the heat removal system was not working properly, the core uncovery and the reactor vessel (RV) failure may be possible.

In this study, the core uncovery and RV failure according to LOCA break sizes were analyzed by using the MAAP4 code when safety injection system (SIS) was not operating normally. We predicted the golden time of SIS recovery for accomplishing the reactor cold shutdown and preventing RV failure. MAAP4 code was used for severe accident analysis. The LOCA simulations were performed with break size in order to predict the golden time to recovery SIS. We predicted the golden time according to the SIS operation cases through the simulation of OPR1000 [1]-[2].

2. Accident scenarios

It was assumed that there were a variety of situations for SIS failure. Accident scenarios were proposed according to break size (0.1%, 1%, …, 100%) relative to the double ended guillotine break (DEGB), and High Pressure and Low Pressure Safety Injection systems (HPSI, LPSI) actuation status in hot-leg LOCA and cold-leg LOCA. It was assumed that safety injection tank (SIT) and Containment Spray System (CSS) were normally actuated [2].

For case 1, it was assumed that the HPSI and LPSI systems were failed in the hot-leg location. It was assumed for case 2 that the HPSI system succeeded and the LPSI system was failed in hot-leg location. For case 3, it was assumed that the LPSI system succeeded and the HPSI system failed in hot-leg location. It was assumed for case 4 that the LPSI system was failed and the HPSI system was not operated at first but operated late in hot-leg location. For case 5, it was assumed that the LPSI system was failed and the HPSI system was delayed in hot-leg location. For case 6 it was assumed that the HPSI and LPSI systems were failed in cold-leg location. For case 7 it was assumed that the HPSI system succeeded and the LPSI system was failed in cold-leg location. For case 8 it was assumed that the LPSI system succeeded and the HPSI system was failed in cold-leg location. For case 9 it was assumed that the LPSI system was failed and the HPSI system was delayed in cold-leg location. Finally, for case 10 it was assumed that the LPSI system failed and the HPSI system was delayed in cold-leg location. For the accident scenarios, the core uncovery time and RV failure time were analyzed. Simulations were conducted according to LOCA break size for each case (Table I).

3. Determining the SIS recovery time

The simulation was divided into the break location, size of the loss of coolant accident (LOCA). The purpose of this study was to predict the golden time for recovering the SIS to prevent the core uncovery and RV failure when SIS is delayed due to problems.

3.1 The influence of the safety injection system at hot-leg LOCA

Fig. 1 shows the core uncovery and RV failure time of the case 1 for the severe accident scenario of hot-leg LOCA. The RV may be damaged because the SIS was not working properly. In case of more than approximately 30% break size of DEGB, core uncovery occurred by the massive coolant leaks. According to the existing research, the passive coolant injection into the reactor vessel by actuation of the SITs in the LOCA (0.5%~2.1%) sequence without active safety injection is able to delay the in-vessel core uncovery progression and reactor vessel failure [3]-[4]. Core uncovery time in the 1% break size of the DEGB is about 435 seconds. Table II shows the core uncovery and RV failure time of the case 1 according to break size.

Fig. 2 shows the core uncovery time of the case 2 for the severe accident scenario of hot-leg LOCA. If the HPSI system is normally operated, RV failure does not occur. The RV failure curve is not shown in Fig. 2. In case of less than 30% break size, it is possible to prevent core uncovery. Table III shows the core uncovery and RV failure time of the case 2 according to break size.

Fig. 3 shows the core uncovery and RV failure time of the case 3 for the severe accident scenario of hot-leg LOCA. When the LOCA break size is less than 3% of

DEGB, cooling water was known not to be injected properly due to the pressure inside the pipe. Also, the reactor core could not be cooled appropriately because of the HPSI failure. The SIS is automatically operated due to the low pressurizer pressure signal (1762 psia) and the high containment pressure signal (1.9 psig). The pressurizer pressure in the 1% of the break size is 2175 psia. Therefore, safety injection signal is not activated at initial time. Table IV shows the core uncovery and RV failure time of the case 3 according to break size.

Fig. 4 shows the core uncovery, RV failure and LPSI delay time of the case 4 for the severe accident scenario of hot-leg LOCA. Even if the LPSI is operated late after a predetermined time, it can be seen that the reactor vessel is not broken. If SIS works normally before the predetermined delay time, the core uncovery and RV failure do not occur [4]-[5]. Table V shows the core uncovery and RV failure time of the case 4 according to break size.

Table VI shows the operating pressure of each system. Fig. 5 shows the pressure and main event time points at 1% break size of DEGB. Since SIT actuation pressure is 4.307 MPa of primary side pressure, SIT can inject cooling water after approximately 461sec. Since LPSI system actuation pressure is 1.258 MPa of primary side pressure, the LPSI can inject cooling water after approximately 802sec.

Fig. 6 shows the core uncovery and RV failure time of the case 5 for the severe accident scenario of hot-leg LOCA. In case of more than approximately 30% break size of DEGB, the RV failure was caused by the delay of the SIS. Table VII shows the core uncovery and RV failure time of the case 5 according to break size.

3.2 The influence of the safety injection system at cold-leg LOCA

Fig. 7 shows the core uncovery and RV failure time of the case 6 for the severe accident scenario of cold-leg LOCA. The reason for core uncovery and the RV failure is because the SIS was not working properly. Table VIII shows the core uncovery and RV failure time of the case 6 according to break size.

Fig. 8 shows the core uncovery time of the case 7 for the severe accident scenario of cold-leg LOCA. In case of less than 60% break size of DEGB in cold-leg LOCA, it is possible to prevent core uncovery if the HPSI actuate on time. Table IX shows the core uncovery and RV failure time of the case 7 according to break size.

Fig. 9 shows the core uncovery and RV failure time of the case 8 for the severe accident scenario of cold-leg LOCA. Table X shows the core uncovery and RV failure time of the case 8 according to break size.

Fig. 10 shows the core uncovery, RV failure and LPSI delay time of the case 9 for the severe accident scenario of cold-leg LOCA. Even if LPSI is operated late but normally before the predetermined time, it is possible to prevent the core exposure and RV failure [5]-[6]. Table XI shows the core uncoveyr and RV failure time of the case 9 according to break size.

Fig. 11 shows the core uncovery, RV failure and HPSI delay time of the case 10 for the severe accident scenario of cold-leg LOCA. In case of more than approximately 60% break size of DEGB, the RV failure occurred due to the delayed actuation of the SIS. Table XII shows the core uncovery and RV failure time of the case 10 according to break size.

4. Conclusions

When LOCA occurred, the normal operation of SIS is very important in maintaining the integrity of NPPs. However if the SIS does not work or its actuation is delayed due to failure of the equipment, the DBA will lead to a severe accident. In this study, accident situations that SIS does not work normally were assumed and a number of MAAP4 code simulations were conducted. In addition, core uncovery time and RV failure time were predicted. If the recovery time of SIS for accident recovery is predicted, the core will not be exposed through appropriate action. Also, the RV failure will be prevented by the cooling water injection even if the reactor core is exposed. These various accident data are thought to be very useful to quickly deal with the actual accident. Also, it will be possible to more efficiently manage accidents beyond design basis for accident recovery.

REFERENCES

[1] Seok Jung Han, Ho Gon Lim, Joon Eon Yang, “Thermal Hydraulic Analysis Aggressive Secondary Cooldown in Small Break Loss of Coolant Accident with Total Loss of High Pressure Safety Injection,” *Proc. of KNS Autumn Mtg*, Seoul, Korea, Oct. 5-11, 2003.

[2] Dea Seop Kim, Soon Ho Park, Ju Hyun Kim , Kwae Hwan Yoo, Man Gyun Na, “Determination of the Recovery Time of Unhealthy SISs in LOCA,” *Proc. of KNS spring Mtg*, Gwangju, Korea, May 30-31, 2014.

[3] S. Y. Park, “Mitigation Effects using Inventory of Safety Injection Tanks for High Pressure Severe Accident Sequence,” *Proc. of KNS spring Mtg*, Taejon, Korea, May 24-25, 2001.

[4] Rae-Joon Park, Kwang-Soon, Hwan-Yeol Kim, Kin-Ho Song, Detail evaluation of safety injection tank effects on in-vessel severe accident progression in a small break LOCA without safety injection, *Annals of Nuclear Energy*, Vol. 58, pp. 54-59, 2013.

[5] Byoung Uhn Bae, Keo Hyoung Lee, Young Soo Kim, Byong Jo Yun, Goon Cherl Park, Scaling methodology for a reduced-height reduced-pressure integral test facility to investigate direct vessel injection line break SBLOCA, *Nuclear Engineering and Design*, Vol. 238, pp. 2197-2205, 2008.

[6] Dong Gu Kang, Seung-Hoon Ahn, Thermal–hydraulic analysis and code assessment for ATLAS 6-inch cold leg break (SBLOCA) test using MARS-KS, *Annals of Nuclear Energy*, Vol. 76, pp. 243-252, 2015.

Table I: Simulation case

Case	Location	SIT Operation	CSS Operation	HPSI Operation	LPSI Operation
1	Hot-leg	Success	Inj & Rec	N/A	N/A
2				Inj & Rec	N/A
3				N/A	Inj & Rec
4				Delay Inj & Rec	N/A
5				N/A	Delay Inj & Rec
6	Cold-leg	Success	Inj & Rec	N/A	N/A
7				Inj & Rec	N/A
8				N/A	Inj & Rec
9				Delay Inj & Rec	N/A
10				N/A	Delay Inj & Rec

Table II: Core uncovery and RV failure times of case 1 (Hot-leg LOCA)

Break Area Max:1.787m²	No LPSI, No HPSI normal	
	Uncovery	RV failure
0.1%	3,404.2	11,092.7
1%	435.8	10,775.2
3%	1,237.8	9,016.7
5%	917.9	8,417.1
10%	663.6	7,950.7
20%	488.0	7,548.3
30%	13.2	7,678.2
40%	11.2	7,604.8
50%	10.1	7,632.5
60%	8.7	7625.0
70%	7.7	7,717.0
80%	6.9	7,676.5
90%	6.2	7,604.3
100%	5.7	7,599.0

Table III: Core uncovery and RV failure times of case 2 (Hot-leg LOCA)

Break Area Max:1.787m²	No LPSI, HPSI normal	
	Uncovery	RV failure
0.1%	-	-
1%	-	-
3%	-	-
5%	-	-
10%	-	-
20%	-	-
30%	13.2	-
40%	11.2	-
50%	10.1	-
60%	8.7	-
70%	8.3	-
80%	6.9	-
90%	6.7	-
100%	6.7	-

Table IV: Core uncovery and RV failure times of case3 (Hot-leg LOCA)

Break Area Max:1.787m²	No HPSI, LPSI normal	
	Uncovery	RV failure
0.1%	3406	11320.7
1%	435.8	60045
3%	-	-
5%	-	-
10%	-	-
20%	-	-
30%	13.2	-
40%	11.2	-
50%	10.1	-
60%	8.7	-
70%	7.7	-
80%	6.9	-
90%	6.2	-
100%	5.7	-

Table V: Core uncovery, RV failure time and delay time of case 4 (Hot-leg LOCA)

Break Area Max:1.787m²	Delay time	No LPSI, HPSI delay	
		Uncovery	RV failure
0.1%	3180	3403.7	-
1%	350	435.8	-
3%	1180	1,237.6	-
5%	860	917.5	-
10%	610	664.7	-
20%	440	488.1	-
30%	7590	13.2	7672.1
40%	7520	11.2	7604.5
50%	7550	10.1	7636
60%	7540	8.7	7634.1
70%	7620	7.7	7733.9
80%	7570	6.9	7762.7
90%	7500	6.2	7638.2
100%	7430	7.7	7626.5

Table VI: Operating pressure of each system

	Operating pressure(Pa)	Primary system pressure(PA)
SIT(Passive)	4.307×10^6 (624.679psi)	1.551×10^7 (2249.543psi)
HPSI	1.258×10^7 (1824.581psi)	
LPSI	1.258×10^6 (182.458psi)	

Table VII: Core uncovery, RV failure time and delay time of case 5 (Hot-leg LOCA)

Break Area Max:1.787m²	Delay time	No HPSI, LPSI delay	
		Uncovery	RV failure
3%	1180	1238	-
5%	860	918	-
10%	610	663.8	-
20%	440	487.2	-
30%	7590	13.2	7677
40%	7510	11.2	7607.8
50%	7540	10.1	7637.6
60%	7520	8.7	7645.3
70%	7600	7.7	7745.7
80%	7560	6.9	7706.4
90%	7490	6.2	7643
100%	7480	5.7	7611.7

Table VIII: Core uncovery and RV failure time of case 6 (Cold-leg LOCA)

Break Area Max:0.912m²	No LPSI, No HPSI normal	
	Uncovery	RV failure
0.1%	7,619.5	16,700.5
1%	1,040.2	24,030.0
3%	5,677.2	15,821.4
5%	3,838.9	13,120.2
10%	2,510.7	11,316.8
20%	1,886.6	10,273.1
30%	1,596.0	9,940.8
40%	1,481.1	9,639.7
50%	1,449.9	9,577.1
60%	12.6	9,621.1
70%	11.5	9,674.7
80%	10.7	9,712.8
90%	10.1	9,760.0
100%	9.7	9,814.0

Table IX: Core uncovery time of case 7 (Cold-leg LOCA)

Break Area Max:0.912m²	No LPSI, HPSI normal	
	Uncovery	RV failure
0.1%	-	-
1%	-	-
3%	-	-
5%	-	-
10%	-	-
20%	-	-
30%	-	-
40%	-	-
50%	-	-
60%	12.6	-
70%	11.5	-
80%	10.7	-
90%	10.1	-
100%	9.7	-

Table X: Core uncovery and RV failure time of case 8 (Cold-leg LOCA)

Break Area Max:0.912m²	No HPSI, LPSI normal	
	Uncovery	RV failure
0.1%	7,619.5	16,700.5
1%	1,040.2	-
3%	-	-
5%	-	-
10%	-	-
20%	-	-
30%	-	-
40%	-	-
50%	-	-
60%	12.6	-
70%	11.5	-
80%	10.7	-
90%	10.1	-
100%	9.7	-

Table XI: Core uncovery, RV failure time and delay time of case 9 (Cold-leg LOCA)

Break Area Max:0.912m²	Delay time	No LPSI, HPSI delay	
		Uncovery	RV failure
0.1%	7460	7,619.4	-
1%	970	1,040.3	-
3%	5640	5,676.4	-
5%	3800	3,839.6	-
10%	2430	2,511.5	-
20%	1810	1,886.6	-
30%	1520	1,595.5	-
40%	1420	1,481.0	-
50%	1390	1,449.5	-
60%	9450	12.6	9,643.4
70%	9500	11.5	9,679.9
80%	9580	10.7	9,738.1
90%	9620	10.1	9,798.2
100%	9860	9.7	9,943.9

Table XII: Core uncovery, RV failure time and delay time of case 10 (Cold-leg LOCA)

Break Area Max:0.912m²	Delay time	No HPSI, LPSI delay	
		Uncovery	RV failure
0.1%			
1%			
3%	5630	5,678	-
5%	3790	3,839.6	-
10%	2430	2,509.3	-
20%	1820	1,886.6	-
30%	1530	1,595.6	-
40%	1420	1,480.3	-
50%	1390	1,449.5	-
60%	9450	12.6	9,666.0
70%	9500	11.5	9,690.6
80%	9550	10.7	9,733.4
90%	9600	10.1	9,763.9
100%	9850	9.7	9,944.3

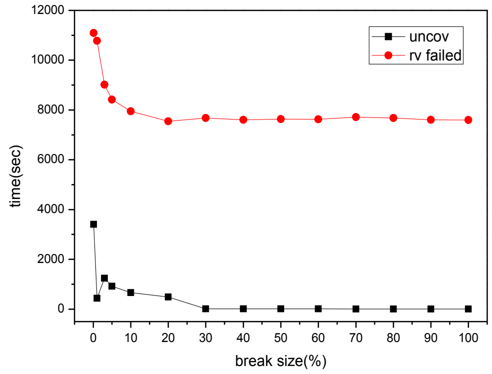


Fig. 1. Core uncovery and RV failure times of case 1 (Hot-leg LOCA)

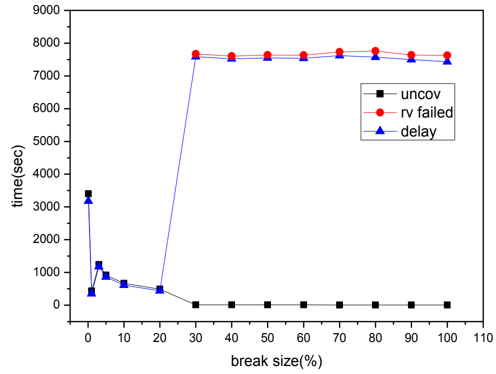


Fig. 4. Core uncovery, RV failure time and delay time of case 4 (Hot-leg LOCA)

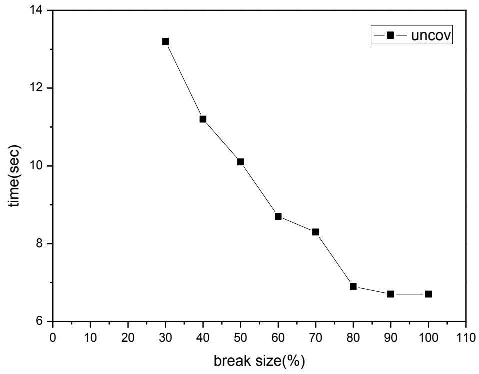
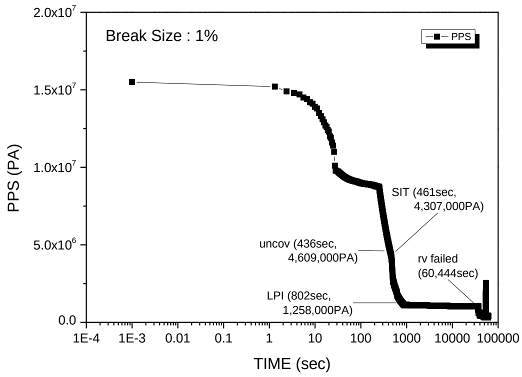


Fig. 2. Core uncovery time of case 2 (Hot-leg LOCA)



(a) Pressure

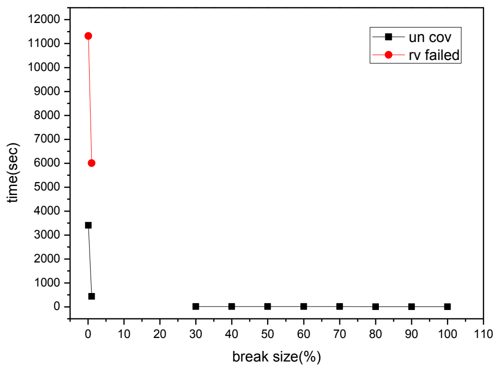
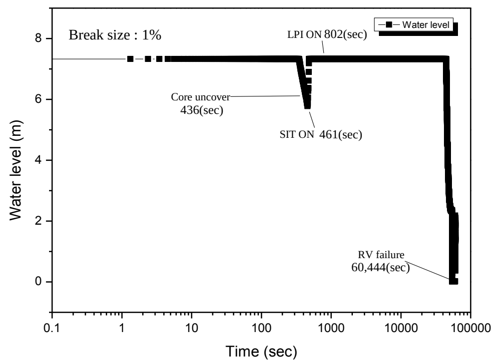


Fig. 3. Core uncovery and RV failure time of case 3 (Hot-leg LOCA)



(b) Main event time points

Fig. 5. Pressure and main points (LOCA 1%)

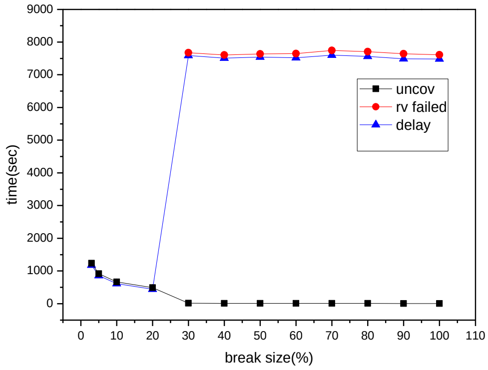


Fig. 6. Core uncovery, RV failure time and delay time of case 5 (Hot-leg LOCA)

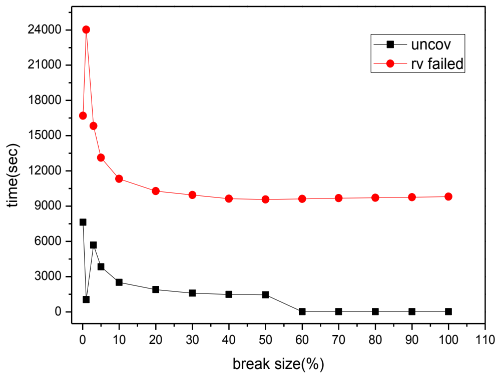


Fig. 7. Core uncovery and RV failure time of case 6 (Cold-leg LOCA)

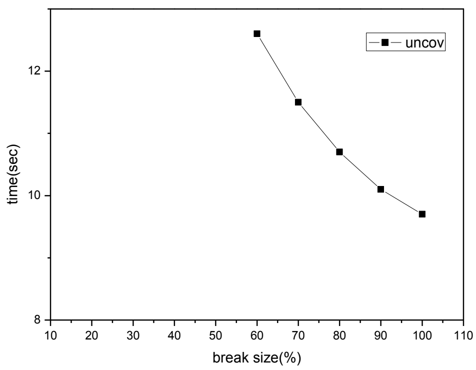


Fig. 8. Core uncovery time of case 7 (Cold-leg LOCA)

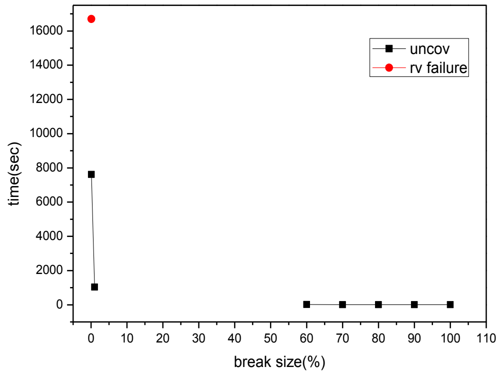


Fig. 9. Core uncovery and RV failure time of case 8 (Cold-leg LOCA)

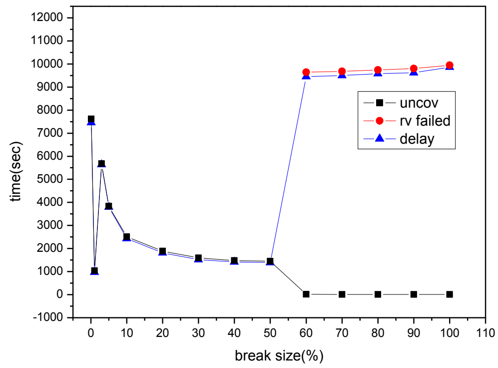


Fig. 10. Core uncovery, RV failure time and delay time of case 9 (Cold-leg LOCA)

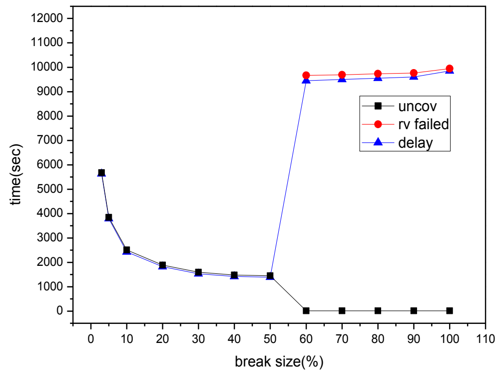


Fig. 11. Core uncovery, RV failure time and delay time of case 10 (Cold-leg LOCA)