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Perspectives on Severe Accident Management by Depressurization and External Water Injection under Extended SBO Conditions

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1. Introduction

A huge tsunami hit the Fukushima nuclear power plant and caused loss of all AC power for a long time (extended SBO). This brought about loss of all cooling functions and hydrogen generated from the metal-water reaction leaked through the drywell and exploded the containment [1]. Three major issues of severe accident management guideline (SAMG) after this sort of extended SBO would be depressurization of the primary system, external water injection and hydrogen management inside a containment [2].

Under this situation, typical SAM actions would be depressurization and external water delivery into the core. However, limited amount of external water would necessitate optimization between core cooling, containment integrity and fission product removal [3].

In this paper, effects of SAM actions such as depressurization and external water injection on the reactor and containment conditions after extended SBO are analyzed using MAAP4 code [4]. Positive and negative aspects are discussed with respect to core cooling and fission product retention inside a primary system.

2. Analysis method

Station blackout with subsequent failure of turbine driven feed water pumps in Kori units 3&4 are simulated using MAAP4 code. The Modular Accident Analysis Program (MAAP) [4] is the fast-running computer code that simulates the response of light water and heavy water moderated nuclear power plants for both current and Advanced Light Water Reactor (ALWR) designs. It can simulate Loss-Of-Coolant Accident (LOCA) and non-LOCA transients for severe accident sequences including actions taken as part of the Severe Accident Management.

The analyses consist of following three types:

- Effect of Depressurization Timing
- Effect of External Water Injection Timing
- Effect of External Water Injection Flow Rates

The first type of analysis is to get insight on the effect of primary depressurization on the reactor and containment failure by adjusting PORV opening time. Two types of opening times are considered such as early- and late-opening: early-opening is to open the PORV after core uncovery and late-opening is to open the PORV after corium re-location occurs.

The second type of analysis is to figure out the effect of external water delivery time to determine core cooling effectiveness. For this analysis, two cases are considered: 8,000 and 13,000 sec.

The third type of analysis is to figure out the effect of external water flow rate to determine core cooling effectiveness and effect on fission product retention. Three flow rates are considered: full flow, 1/2 full flow and 1/4 full flow rates.

Also, it is assumed that the amount of external water source is limited and it is the same as the amount of refueling water.

3. Result and discussion

3.1 Effect of Depressurization Timing

Table 1 shows the event log of the SBO scenario for two kinds of depressurization timing. In the early-open case the two PORVs were opened just after core uncovery (6,800 sec) and in the late-open case, two PORVs were opened when corium relocates at the lower plenum (11,000 sec).

Table 1. Effect of Depessurization Time

	SBO	Early-Open	Late-Open
Events	Time(s)	Time(s)	Time(s)
Core Uncovery	6,767	6,767	6,767
Opening PORV 2 (Early)	-	6,800	-
First Corium Relocation	10,900	11,246	10,900
Opening PORV 2 (Early)	-	-	11,000
Reactor Vessel failure	11,820	20,609	12,444
SIT Delivery	11,829	8,295	11,881
SIT Exhaust	11,858	20,636	12,477
Containment Failure	39,027	48,580	75,107
66 hr CsI Release	4.17E-02	1.68E-01	3.17E-02

Two conflicting results are obtained. When we depressurize earlier, delivery of SIT flow is expedited than late opening and thus reactor vessel failure timing is delayed. However, due to early pressurization of containment by steaming SIT water in the core, the containment failure occurs earlier. On the other hand, for the late PORV opening, i.e., after first core relocation, the reactor vessel fails earlier by about 8000 sec than early opening but the containment failure is significantly delayed by about 28,000 sec than the early opening. Fig. 1 shows the containment pressure variation for the three cases including the base case without depressurization.

As shown in Fig. 1, after SBO occurs, the containment pressure increases by steam release to the containment from the PSV and PORV. And after reactor vessel failure, containment pressure increases by molten-core-concrete interaction (MCCI) but the pressure excursion rate is much slower than that by the steam release from the primary system through PORV opening.

With respect to fission product release, however, 66 hr CsI release is significantly increased for the early opening over the base case, but for the late opening total CsI release is comparable to the base case (do nothing) even though reactor vessel failure is not much delayed after the base case.

It can be thus concluded that the early depressurization action itself under extended SBO has two-faces: positive with respect to delay of the reactor vessel failure but negative with respect to the containment failure and fission product retention inside the primary system

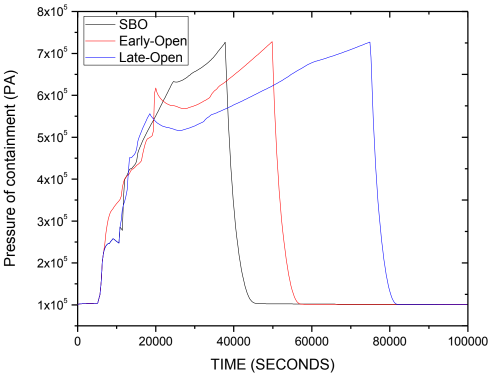

Fig. 1 Effect of depessurization time on containment pressure

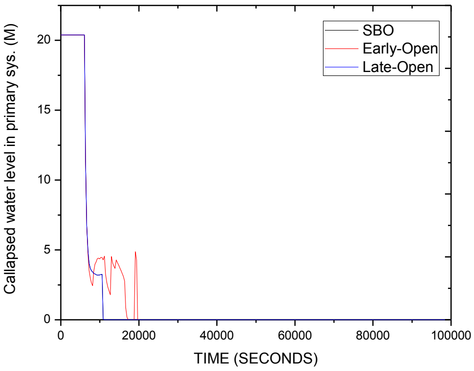

Fig. 2 Effect of depessurization time on primary system collapsed water level

3.2 Effect of External Water Injection Timing

Table 2 shows the effect of external water delivery timing after early opening of PORVs at 6,800 sec. Two cases considered are: external water delivery starting at 8,000 and 13,000 sec which are delayed by 1200 and 6400 sec after 2 PORV depressurization, repectively. Full flow of external water corresponding to a high pressure injection pump is assumed.

Table 2. Effect of External Water Delivery Timing

	SBO	EW1	EW2
Events	Time(s)	Time(s)	Time(s)
Core Uncovery	6,766	6,766	6,766
Opening PORV 2 (Early)	6,800	6,800	6,800
External Water Delivery	-	8,000	13,000
First Corium Relocation	10,999	66,831	10,999
Reactor Vessel failure	18,877	No	No
SIT Delivery	8,289	8,237	8,289
SIT Exhaust	18,912	15,808	24,331
Containment Failure	49,796	83,997	87,802
66 hr CsI Release	1.68E-01	1.11E-01	9.86E-02

For all these cases, reactor vessel failure does not occur. However containment fails due to pressurization by the steam from boiling of water in the core without containment spray that would have condensed the steam if available. However, the containment failure time is not very sensitive to the external water delivery starting time as shown in Table 2 and Fig. 4.

This can be explained from Figs. 3, 4 which show the primary and containment pressure variations for each case: After SBO occurs, containment pressure increases by PSV cyclic opening and subsequently from PORV after depressurization at 6,800 sec (Fig. 2) but after that, SIT flow is delivered into the core and the containment pressurization (see Fig. 4) is a little suppressed by the cooling effect of the SIT water which has been delivered until 15,808 and 24,331, for the two cases.

After SIT water is exhausted, containment pressure increases more slowly for the late injection case (line EW2 in Fig. 4) than early injection case (line EW1 in Fig. 4). This is because decay power for the early late injection case is larger than the decay power for the late injection case.

However, after 65,000 sec, the external water source is exhausted due to limited amount and the primary water level decreases as shown in Fig. 5. And the containment pressure increases further since the steam continuously generated from remaining water in the core releases through the open PORV. Thus, in order to prevent containment overpressure failure, re-closing of the PORV should be considered. Late injection of external water may be a little more positive since the CsI release into the containment is less than early-injection as shown in Table 2.

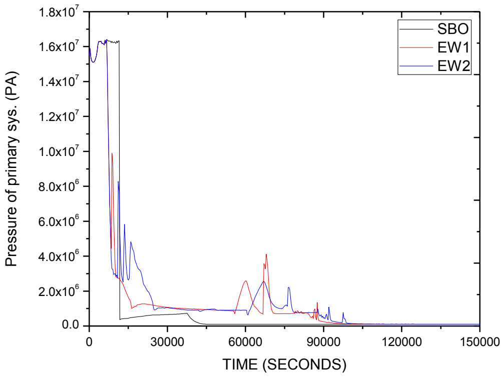

Fig. 3 Effect of external water starting time on primary pressure.

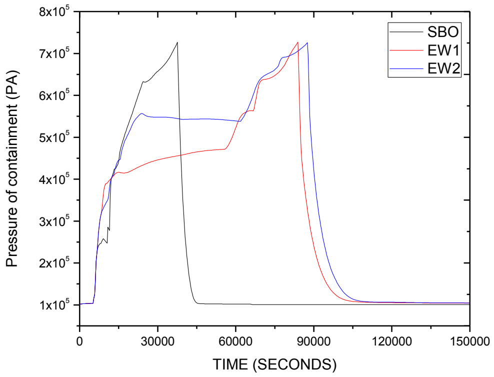

Fig. 4 Effect of external water starting time on containment pressure.

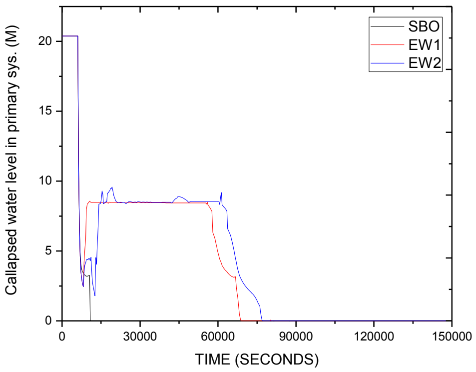

Fig. 5 Effect of external water starting time on primary system collapsed water level

3.3 Effect of External Water Injection Flow Rates

As the third type of analysis, effects of external water injection flow rates on the core cooling and fission product retention are studied. For all the cases, external water injection is started at the same time, i.e., just after first corium relocation into the lower plenum. Three flow rate cases are considered: full flow, 1/2 full flow and 1/4 full flow rates.

Table 3. Effect of External Water Injection Flow Rate

	SBO	Full Flow (FF)	1/2 Full Flow (F1/2)	1/4 Full Flow (F1/4)
Events	Time(s)	Time(s)	Time(s)	Time(s)
Core Uncovery	6,766	6,766	6,766	6,766
Opening PORV 2 (Early)	6,800	6,800	6,800	6,800
First Corium Relocation	10,999	10,999	10,999	10,999
External Water Delivery	-	11,000	11,000	11,000
Reactor Vessel failure	18,877	No	230,492	233,539
SIT Delivery	8,289	8,289	8,289	8,289
SIT Exhaust	18,912	20,025	120,330	216,623
Containment Failure	49,796	87,112	34,690	27,823
66 hr CsI Release	1.68E-01	9.83E-02	6.87E-02	1.00E-02

For the full injection flow case, reactor vessel failure does not occur. However, for the 1/2 and 1/4 flow rate cases, reactor vessel fails but the instances are 230,492 and 233,539 sec and they are not so different from each other as shown in Table 3. This shows that injection flow rate is not important for a delay of reactor vessel failure.

On the other hand, containment failure timing and the total CsI release into containment is very different for each case as shown in Table 3. Containment failure occurs latest in the full flow case (FF in Table 3) and earliest in the 1/4 flow case (F1/4 in Table 3). This can be easily expected since the full flow case delivers most sufficient cooling water earlier to cool the core and suppress steam generation and release into the containment as shown in Fig. 7.

However, because the amount of external water is limited, the duration of water injection into the core is shorted in case of full flow as shown in Fig. 8. Therefore, the primary water level persists longer for the 1/4 flow case than the full flow case as shown in Fig. 9 and thus fission product scrubbing effect is much better. Therefore, total 66 hr release of CsI into the containment is largest in case of full flow case and lowest in case of 1/4 flow rate as presented in Table 3.

It can be thus concluded that in case of the external water injection, the flow rate should be optimized considering not only the cooling effect but also the long term fission product retention inside the primary system.

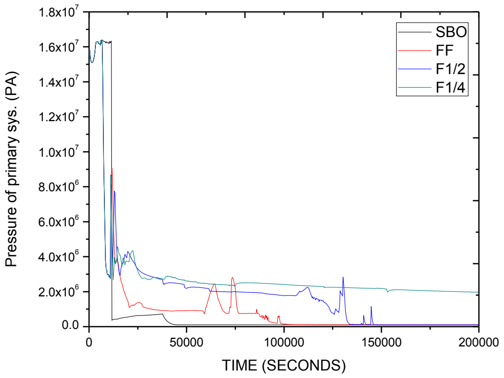

Fig. 6 Effect of external water flow rate on primary pressure.

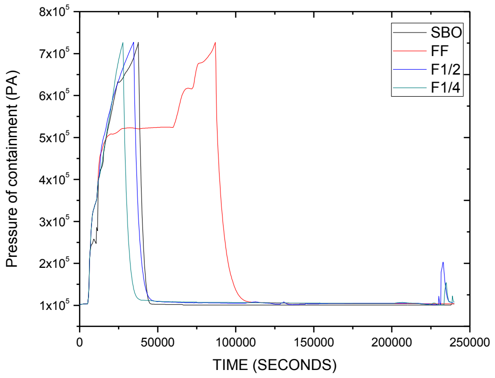

Fig. 7 Effect of external water flow rate on containment pressure.

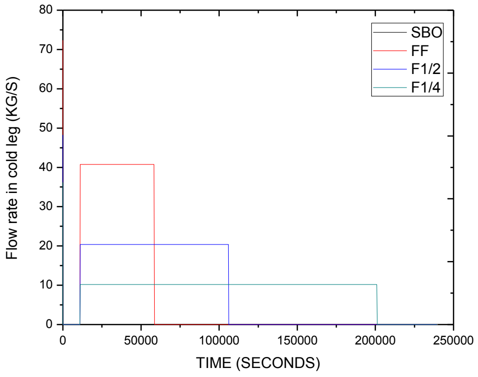

Fig. 8 External water injection flow rates.

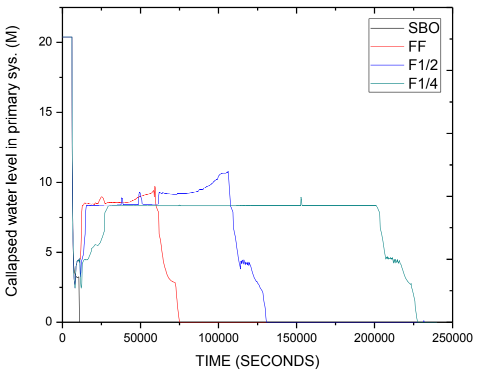

Fig. 9 Effect of external water flow rate on primary system collapsed water level

4. Conclusion

Effects of SAM actions such as depressurization and external water injection on the reactor and containment conditions after extended SBO are analyzed using MAAP4 code and pros/cons are discussed with respect to core cooling and fission product retention inside the primary system. Conclusions are made as following: Firstly, early depressurization action itself has two-faces: positive with respect to delay of the reactor vessel failure but negative with respect to the containment failure and fission product retention inside the primary system. Secondly, in order to prevent containment overpressure failure after external water injection, re-closing of PORV later should be considered in SAM, which has never been considered in the previous SAMG. Finally, in case of external water injection, the flow rate should be optimized considering not only the cooling effect but also the long term fission product retention inside the primary system.

Acknowledgements

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5. References

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