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Sensitivity Analysis on Operator Actions for MSGTR Accident Mitigation using RELAP5/MOD3.3

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1. Introduction

The safety evaluation of Nuclear Power Plants (NPPs) for multiple failure accidents such as Multiple Steam Generator Tube Rupture (MSGTR) and the verification of the adequacy of accident mitigation measures have gained importance after the Fukushima accident in 2011. Compared to Steam Generator Tube Rupture (SGTR), MSGTR accident proceeds rapidly because of the high discharge flow, and thus suitable operator actions are essential to mitigate the accident and prevent the release of radioactive materials into the outside. In order to mitigate the accident successfully, it is crucial for the operators to identify MSGTR early and perform each operator action within the allotted time.

According to the relevant Emergency Operation Guidelines (EOGs), the main operator actions for MSGTR mitigation are as follows: (1) Reactor Coolant Pump (RCP) manual trip and restart, (2) steam discharge to the condenser and RCS temporary-cooldown using Steam Bypass Control System (SBCS) manual control with the Main Steam Isolation Bypass Valve (MSIBV) opening, (3) RCS depressurization for pressure balance of Pressurizer (PZR) and affected SG using the PZR aux-spray, and (4) RCS controlled-cooldown using Main Steam Atmospheric Dump Valve (MSADV) of the unaffected SG.

In this study, the way and required time for major operator actions were derived through sensitivity analyses. The reference plant is 2-loop 1000 MWe Pressurized Water Reactor (PWR), and analyses were performed using RELAP5/MOD3.3 [1].

2. MSGTR Analysis Modeling

Figure 2 shows the nodalization for MSGTR analysis. It consists of primary side, secondary side, and safety systems. Also, the operator actions for mitigation of accident were considered on this analysis. Thus, the analysis model contained PZR Pressure Control System (PPCS), PZR Level Control System (PLCS), Feedwater Control System (FWCS), and SBCS. Additionally, MSIBV, PZR aux-spray, MSADV, and SG Blowdown (SGBD) were also added. Following realistic assumption for MSGTR analysis, the nominal values at full power (100 %) condition were set to be the initial and boundary conditions.

It was assumed that 5 tubes are instantaneously broken in the hot-leg side of SG-2 at 0 sec. The rupture was modeled as double-ended guillotine break. In the base case calculation, it was assumed that the first operator action, the RCP trip, is performed 10 min after the reactor trip. Afterward, it is assumed that the operator conducts a procedure of actions to mitigate the MSGTR 15 min after the reactor trip [2]. The operator action time for each procedure was considered to be 2 min. The calculation result of base case is presented in reference [3].

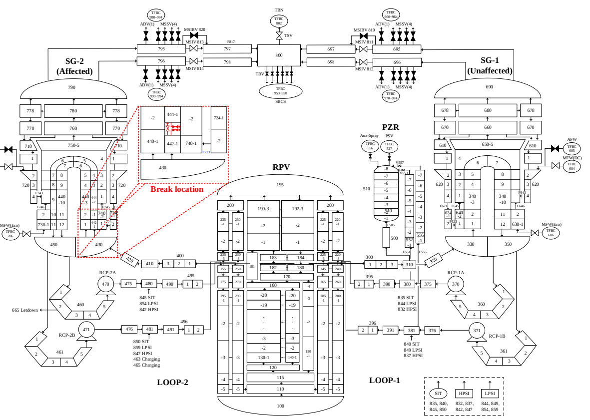

Fig. 1. RELAP5 nodalization for MSGTR analysis

3. Sensitivity Analysis Results on Operator Actions

The operator actions for mitigating the MSGTR accident mainly composes as follows: (1) RCP manual trip, (2) RCS temporary-cooldown using MSIBV and SBCS, (3) PZR aux-spray operation, (4) RCS controlled-cooldown using ADV, and (5) RCP restart. In order to mitigate the accident effectively, the operator have to take each action within the appropriate time. The sensitivity analyses were performed to investigate the effect of each operator action on accident mitigation.

3.1 RCP Manual Trip

In MSGTR base case analysis of this study, all 4 RCPs are stopped in 10 min after the reactor trip according to PZR pressure set-point as well as RCS subcooling. In the event of MSGTR accident, considering the complicated state of NPP, there may be differences in the number of tripped RCPs (2 or 4) by the operator. Since the initial response to prevent the MSSV opening is important and the RCP manual trip is the first operator action. So it is necessary to examine the effect of this action.

Figure 2 shows the RCS pressure following the RCP manual trip. When only 2 RCPs are stopped, the forced circulation flows to both SGs are continuously maintained and the RCS pressure decreases quickly. On the other hand, in the base case, the RCS pressure slowly decreases because all 4 RCPs are tripped. However, after the restart of 2 RCPs at 6,338 sec, the RCS pressure rapidly decreases to reach the SCS entry condition.

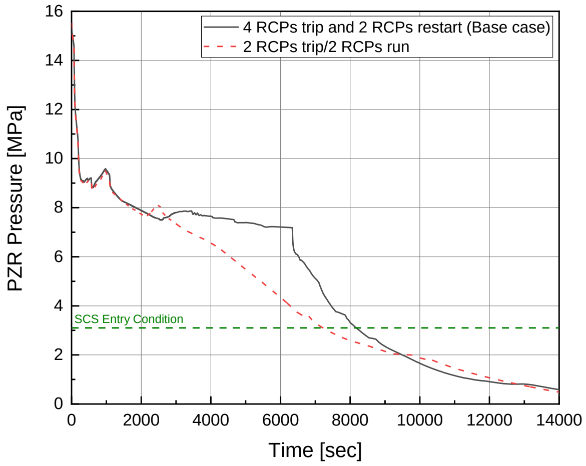

Fig. 2. Sensitivity analysis results for RCP manual trip

3.2 RCS Temporary-Cooldown Operation

After the RCP manual trip, the operator conducts the RCS temporary-cooldown operation using SBCS to prevent the opening of MSSV on the affected SG. This operation is the first key action in the early stages of the MSGTR accident. If it is carried out late, the MSSV will be opened. Therefore, analysis regarding the opening time of MSSV for each number of ruptured tubes (1, 2, 5, and 10) without operator action was performed. And we investigated the initiation time when the RCS temporary-cooldown operation was required during MSGTR.

Figure 3 presents the accumulated MSSV flow by the number of ruptured tubes when there is no operator action. The MSSV opening times are as follows: 2090 sec (1 tube), 1574 sec (2 tubes), 1090 sec (5 tubes), and 976 sec (10 tubes). In case of SGTR, MSSV opening occurs about 22 min after the reactor trip (i.e. 35 min), whereas during MSGTR (10 tubes), MSSV opening occurs about 15 minutes after the reactor trip (i.e. 16 min). It can be seen that the RCS temporary-cooldown operation in MSGTR needs to be performed within 15 min after the reactor trip and more promptly than in SGTR.

3.3 PZR Spray Operation

The RCS temporary-cooldown operation can prevent the MSSV opening in the early stages of the accident. However, when this operation is terminated, the RCS and the affected SG are re-pressurized. The PZR spray operation is action to reduce the pressure difference between the PZR and affected SG. It is necessary to reduce the break flow to the affected SG and prevent the MSSV opening by the RCS depressurization. Therefore, this section examined the effect of PZR aux-spray operation time (10, 20, 30, 40, and 50 min delay compared to the base case), and investigated the required time.

Figure 4 shows the pressure behavior of the PZR and affected SG. The PZR and affected SG pressure start to increase when the RCS temporary-cooldown operation is terminated. If the PZR spray operation is delayed by more than 30 min than the base case (i.e. 2 minutes after the RCS temporary-cooldown start), the affected SG pressure reaches the MSSV opening set-point along with high break flow. From the sensitivity analysis results, it is found that the PZR spray operation needs to be performed within about 47 min after the reactor trip (i.e. 32 min after the RCS temporary-cooldown start).

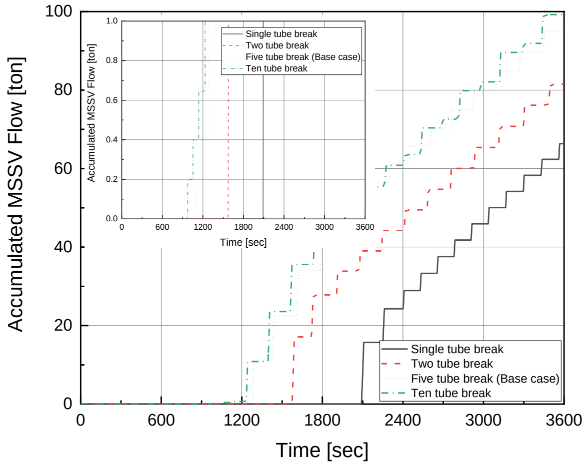

Fig. 3. Sensitivity analysis results for RCS Temporary-Cooldown Operation

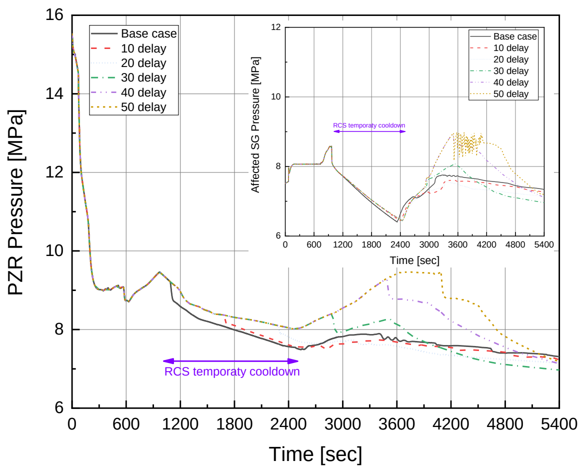

Fig. 4. Sensitivity analysis results for PZR spray operation

3.4 RCS Controlled-Cooldown Operation

When the RCS temporary-cooldown operation is terminated, the operator clearly identifies and isolates the affected SG. And then, the operator opens the ADV of the unaffected SG for RCS controlled-cooldown operation. After the end of the RCS temporary-cooldown operation, pressure of both SGs increases again. But when the RCS controlled-cooldown operation is started, the affected SG is depressurized together with the RCS. This section examined the effect of ADV operation time (5, 10, 15, 20, 25, and 30 min sensitivity to base case) on accident mitigation.

Figure 5 shows the pressure behavior according to the ADV opening time. As the RCS controlled-cooldown is delayed, the RCS pressure increases and the required time to reach the SCS entry conditions increases. If the RCS controlled-cooldown operation is delayed by more than 15 min than the base case (i.e. 6 min after the end of the RCS temporary-cooldown), the MSSV of affected is opened. It can be seen that the start time of the RCS controlled-cooldown operation is important. In conclusion, it is determined that the RCS controlled-cooldown operation needs to be taken within 15 min after the RCS temporary-cooldown operation is completed.

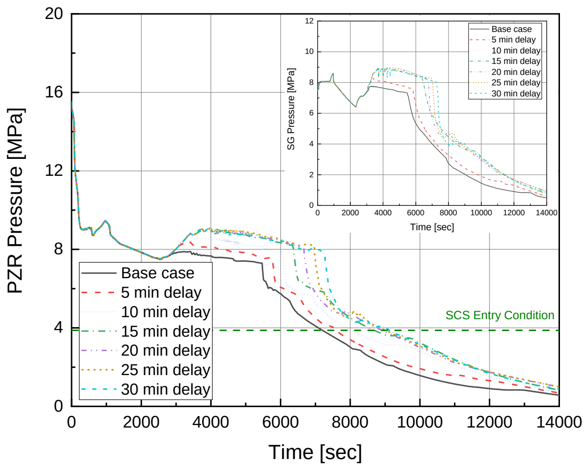

Fig. 5. Sensitivity analysis results for RCS Controlled-Cooldown Operation

3.5 RCP Restart

The operator conducts RCS controlled-cooldown using ADV of the unaffected SG. However, the RCS depressurization by natural circulation cooling does not proceed quickly. In this case, forced circulation cooling by RCP is required to effectively depressurize the RCS to the SCS entry condition. The operator checks the appropriateness of conditions for RCP restart and restarts the RCPs. The depressurization of RCS would depend on the restart time and the number of RCPs. Therefore, this section examined the effect of the time of RCP restart (30, 60, and 90 min after the ADV opening) and the number of RCPs (0, 1, and 2 at 1 hr after ADV opening).

Figure 6 shows the pressure behavior according to the RCP restarting time. The RCS pressure decreases immediately after the RCP restart. Also the faster the restart, the faster the SCS entry condition is reached.

Figure 7 shows result about the number of RCPs restart. Even without the restart of RCP, the RCS temperature continues to decrease because of natural circulation cooling by the RCS controlled-cooldown operation. However, the RCS pressure does not decrease much in spite of the PZR aux-spray. It may be seen that the RCP restart operation is necessary to reach the SCS entry condition quickly.

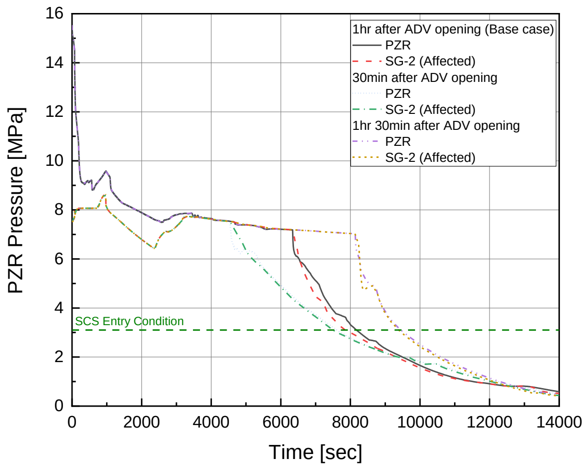

Fig. 6. Sensitivity analysis results for RCP Restart (Time of RCP restart)

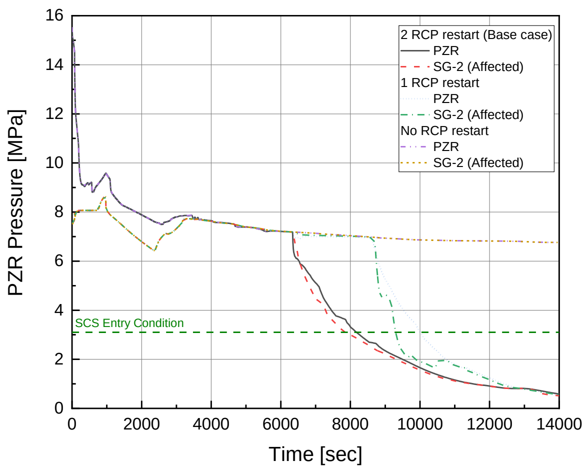

Fig. 7. Sensitivity analysis results for RCP Restart (The number of restarted RCPs)

4. Conclusions

Because MSGTR progresses quickly due to higher break flow rate than in SGTR, the appropriate operator action is crucial to mitigate the accident and prevent the release of radioactive materials. So that effectively mitigate the accident, it is necessary for the operator to properly perform each operator action within the appropriate time. In this study, the way and required time on major operator actions are deduced through sensitivity analyses using the RELAP5/MOD3.3 code. The results of this study offer insight into the effect of each operator actions for mitigation of MSGTR accidents and their importance. Thus, these findings could be applied importantly to use the accident mitigation strategy and the training of operator for MSGTR.

ACKNOWLEDGEMENT

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