Development of Long-term Cooling Operation Strategy with H-SIT

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1. Introduction

In the current nuclear power plants (NPPs), most of the critical safety functions are provided by many active safety systems [1]. However, in order to meet the futuristic goals of safety, relying on these active safety systems alone does not seem to be viable. As passive system has a strength on the mitigation of station black out accident and it also contributes to increase the diversity of mitigation way, application of passive system becomes a paramount in the nuclear industry to enhance the nuclear plant safety.

General passive systems and strategies, however, have a critical limitation, especially for passive injection systems. As these systems use gravity as their driving force, it is difficult to inject coolant in a passive way in a high-pressure condition thus depressurization has to be preferentially performed to do passive injection. The problem is that depressurization inevitably causes the loss of core inventory thus it is not preferred in order to secure plant safety.

Hybrid safety injection tank (H-SIT) system was newly suggested a few years ago to passively inject the coolant into the reactor coolant system (RCS) without depressurization in a high-pressure condition [2]. The H-SIT system is planned to be integrated into advanced power reactor plus (APR+). Generally, the H-SIT system can inject water using the pressure from nitrogen gas as a conventional safety-injection tank in low-pressure accidents, such as large and medium-break loss of coolant accidents (LOCA). Additionally, the H-SIT system can also inject water using gravitational force in high-pressure accidents. If a high-pressure accident occurs, the pressure of each H-SIT is equalized with pressure of pressurizer through equalizing pipes, thus allowing the H-SITs to inject water by gravitational force. In the target plant, four H-SITs are planned to be installed. Each has a 2.5in diameter equalizing pipe and it can be operated manually. Figure 1 shows conceptual layout of the H-SIT system.

Long-term cooling of core is an ultimate goal of all mitigation actions for plant safety and feed and bleed (F&B) operation strategy is one of long-term cooling strategies in conventional pressurized water reactor (PWR). The important point of F&B operation is that, in conventional mitigation strategy, injection for feed operation is performed by only high pressure injection (HPSI) pump. Low pressure injection (LPSI) pump such as shut down cooling pump (SCP) cannot be used for F&B operation. Thus, when F&B operation is needed, if high-pressure injection pump fails, core should be damaged. This limitation of the F&B strategy can be checked in conventional event tee of SLOCA as figure 2.

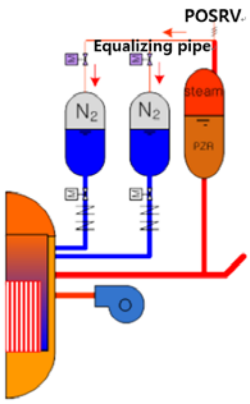

Fig. 1 Outline of an H-SIT system

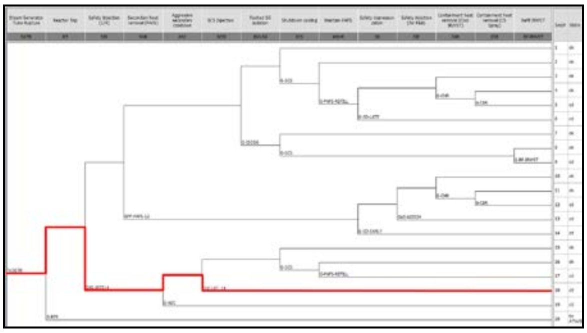

Fig. 2 Event tree model of SLOCA

As H-SIT is passively operated in an accident situation, it was originally designed for mitigation of station black out accident. Besides, operator can use the H-SIT system same as high pressure injection pump in any accident situations. Thus, function of high pressure injection by H-SIT can be used for feed operation when HPSI pumps fail. If it is possible, H-SIT can make up the core during depressurization then LPSI pumps can be used for F&B operation.

2. F&B operation strategy using LPSI with H-SIT

As mentioned in introduction, F&B operation strategy is generally performed by HPSI pumps in the conventional mitigation strategy. Thus, if F&B operation strategy using LPSI with H-SIT is added into conventional F&B strategy, it has higher reliability for its success thus it can enhance plant safety significantly.

2.1 Limitation of F&B Operation Strategy with H-SIT or LPSI alone

In case of H-SIT system, even though it can be used same as high pressure injection pump in the accident situation, it cannot be used for the long-term cooling because it has limited coolant inventory. It just suitable for temporary high pressure injection. For this reason, H-SIT system alone cannot be used for long-term cooling operation.

In APR+, there are two shutdown cooling pumps (SCPs) and two containment spray pumps (CSPs) which can be used as a LPSI pump. However, all four pumps are not used for F&B operation due to low injection pressure of the pumps. Generally, LPSI pump can be operated around 20bar. For F&B operation with LPSI, RCS pressure should be decreased until 20bar. As an example, when LOCA occur and HPSI pump is failed, RCS pressure decreases continuously. However, the problem is core level also decreases due to inventory loss through break part. Figure 3-1 shows that at 2800s after accident occur, core exit temperature (CET) is higher than severe accident entry condition (922K) [3].

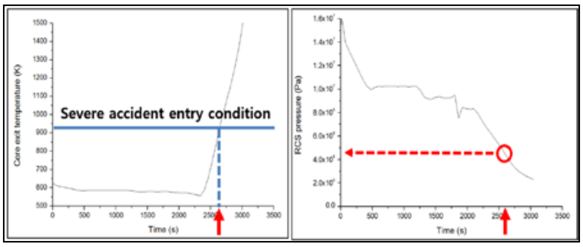

Fig. 3 Core exit temperature and RCS pressure when bleed operation is performed

At this time, based on figure 3-2, RCS pressure is still around at 40bar which is too high to use LPSI pump. That is the main reason why LPSI pump cannot be used for F&B operation. In this situation, as H-SIT can be used as a high pressure injection system, it can make up core inventory during bleed operation thus core is safely depressurized until LPSI pump injection pressure. If it happened, LPSI injection for F&B operation can be used. In this way, conceptually, H-SIT can be used for long-term cooling with LPSI.

2.2 Development of F&B Operation Strategy using LPSI with H-SIT

2.2.1 F&B Operation Strategy with Depressurization using POSRV

Generally, operator can decrease the RCS pressure by opening the pilot operated safety relief valve (POSRV) for bleed operation [4]. Thus, F&B operation strategy with H-SIT is firstly tried to develop using POSRV. However, this strategy has the critical problem that is injection failure of H-SIT system. When POSRV open, a lot of steam release through POSRV while there is no mass flow inside of equalizing pipe. Because, structurally, equalizing pipe of H-SIT is closely connected with POSRV and area of POSRV is relatively larger than area of equalizing pipe. If there is no flow inside pipe, pressure between H-SIT and pressurizer is not equalized well thus H-SIT cannot inject water into RCS. In figure 4-1 show the mass flow rate of equalizing pipe. In this figure, mass flow rate when POSRV continuously open is lower than flow rate of equalizing pipe in normal situation. Even back flow which is from H-SIT to pressurizer is occurred. For this reason, as we can see in figure 4-2, level of H-SIT do not decrease thus this strategy cannot be used for F&B operation with LPSI thus another depressurization system have to be found to use H-SIT during F&B operation.

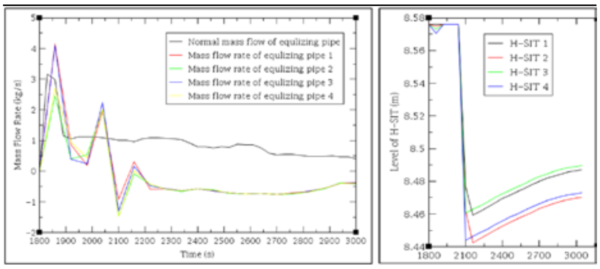

Fig. 4 Mass flow rate and level of H-SIT when POSRV is used for bleed operation

2.2.2 F&B Operation Strategy with Depressurization using RCGVS

Based on the final safety analysis report of APR1400, bleed operation for F&B operation can be performed by not only POSRV but also reactor gas venting system (RCGVS). Thus, in order to use H-SIT during bleed operation, RCGVS is used for bleed operation as an alternative system of POSRV. When bleed operation is performed using RCGVS, H-SIT can inject water well thus core is filled again with the coolant from H-SIT. However, this strategy has also one problem that is it takes too long time to depressurize the RCS pressure enough for low pressure injection by RCGVS only. In figure 5, at 7000s after accident occur, RCS pressure is below than 20bar thus it is satisfied to inject water using LPSI. Problem, however, is that 7000s is too long to make up core using temporary injection by H-SIT only. Thus, core is dried out and CET is above than severe accident entry condition (922K) [3]. Therefore, this strategy cannot be used for F&B operation with LPSI and additional depressurization is needed.

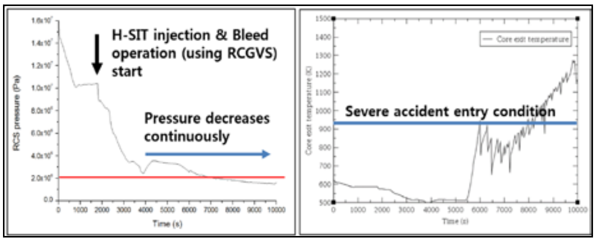

Fig. 5 RCS pressure and CET when RCGVS is used

2.2.3 F&B Operation Strategy with Depressurization using RCGVS and POSRV together

As previously mentioned, POSRV cannot be used for F&B operation due to failure of pressure equalizing between H-SIT and pressurizer. That means, in other word, if we don't need to consider operation of H-SIT, POSRV can be used for depressurization. Based on this thermal hydraulic analysis, H-SIT is dried out around 3000s after accident occur. That is also reason why decrease rate of pressure suddenly changed around 3000sec in figure 5. Thus, when H-SIT is dried out, we don't need to consider of pressure equalizing between H-SIT and pressurizer thus POSRV can be used together with RCGVS as additional way of bleed operation. When POSRV is used, RCS pressure decreases well thus SCP start to inject water around 3300s. Figure 6 shows the RCS pressure according to sequence of F&B operation strategy with LPSI and H-SIT system.

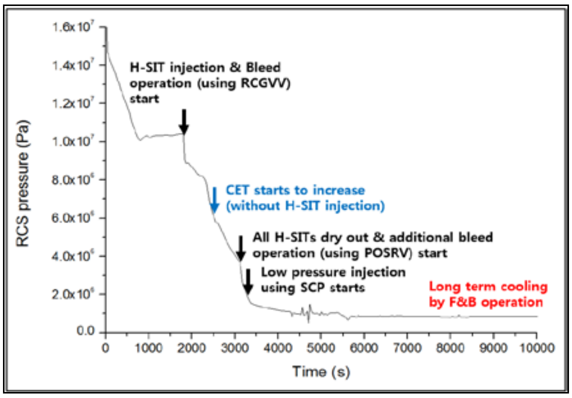

Fig. 6 Change of RCS pressure according to sequence of F&B operation strategy with LPSI and H-SIT

As in figure 7, based on thermal hydraulic analysis, when operator use this F&B operation strategy, core level is maintained around 100% and CET is stable during operation. Therefore, in this study, this strategy is decided as the final strategy for feed and bleed operation using LPSI with H-SIT.

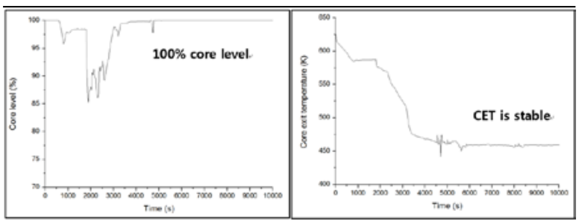

Fig. 7 Core level and CET when F&B operation is successfully applied

3. Risk Analysis of the Long-term Cooling Strategy with H-SIT System

In this section, risk analysis of new F&B operation strategy is performed to analyze the effect of strategy. For this analysis, PSA methodology is used to calculate the change of core damage frequency when new F&B operation strategy is applied.

3.1 Event tree Model Development

Revised event tree model is developed based on the F&B operation strategy with LPSI and H-SI. Figure 8 show the event tree model of small LOCA as an example. In addition, this strategy can be used in all accident cases except medium and large LOCA. In this figure, low pressure F&B operation strategy can be used at two points. Both points are the case in which PAFS and SIP are all failed.

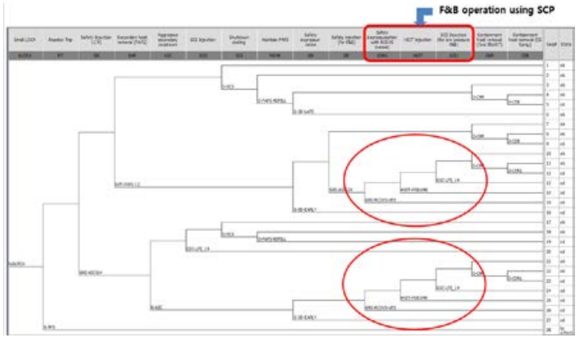

Fig. 8 Revised event tree model of SLOCA

3.2 Fault tree Model Development

In order to calculate the result from revised event tree model, branch probability have to be firstly calculated by making the detailed fault tree model. In order to develop those fault trees, minimum requirement for success of F&B operation preferentially defined based on the thermal hydraulic analysis in this study.

In case of F&B operation with LPSI and H-SIT, mainly three variables have to be considered to guarantee success operation. Those are number of depressurization valves, H-SITs and low pressure injection pumps because those three are the only components which are used for F&B operation strategy with LPSI and H-SIT. Thus, if those three variables are satisfied with its minimum requirement, F&B operation can be certainly well performed without any problems.

In case of number of valves, minimum requirement is two RCGVSs and two POSRVs. If this requirement is not satisfied, pressure of RCS don't decrease below 20bar thus LPSI pumps cannot inject coolant into RCS and CET increases dramatically when H-SIT is dried out as figure 9.

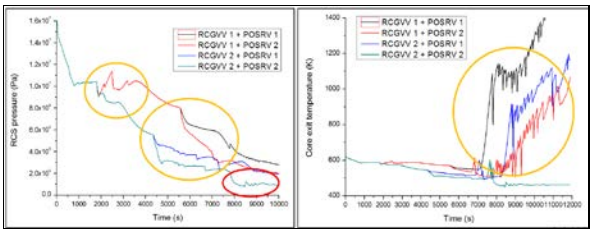

Fig. 9 RCS pressure and CET according to number of valves

In case of number of SITs, four H-SITs are the minimum requirements. When four H-SITs are used at same time, CET is stably maintained. If not, CET increase above than severe accident entry condition because H-SIT cannot make up inventory perfectly.

In case of low pressure injection pumps, only one LPSI is enough to make up core inventory during F&B operation. Thus, one LPSI is set as a minimum requirement.

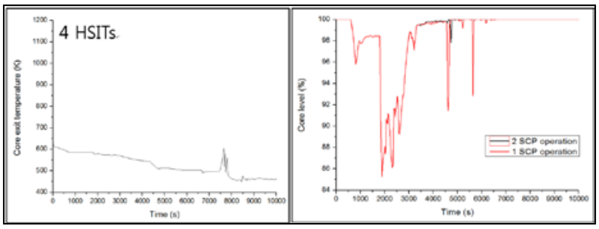

Fig. 10 CET and core level when four H-SITs and one LPSI is used for F&B operation

Finally, fault tree model is developed based on the minimum requirements of three variables. As an example, figure 11 shows the fault tree model for bleed operation using RCGVS. Thus, finally, change of core damage frequency can be calculated in order to analyze the effect of new F&B strategy for plant risk.

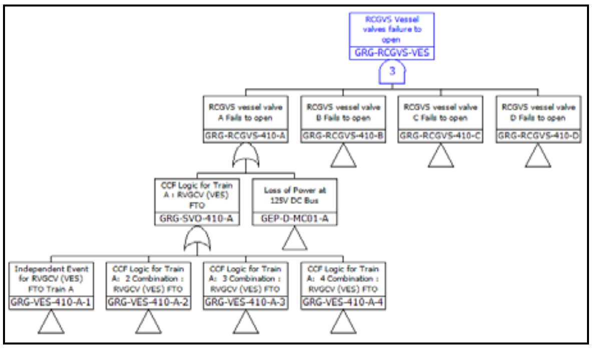

Fig. 11 Fault tree model for bleed operation using RCGVS

3.3 Core damage frequency calculation

In order to do core damage frequency (CDF) calculation, AIMS program which is developed by KAERI (Korea atomic energy research institute) is used and reference PSA model of APR+ is also referred from KAERI.

According to the reference PSA model, CDF of APR+ is 2.010e-6. It is quite reasonable amount for nuclear safety. If new F&B strategy with H-SIT is applied, CDF fall to 1.868e-6 which declined 7 percent from the reference model because this new strategy can decreases CDF of specific sequence in which PAFS and SIP are all failed. Originally, if PAFSs and SIPs are all failed, core is inevitably failed. Whereas, if H-SITs exist in the NPPs, in order to do F&B operation, operator can use SCPs or CSPs even SIPs are all failed. It means F&B operation strategy with LPSI and H-SIT can successfully enhance the plant safety.

4. Conclusion

In this study, F&B operation strategy with LPSI and H-SIT is developed. This is a new concept for the long-term cooling operation. If this strategy is applied, low pressure injection pump can be successfully used for F&B operation thus operator has the additional mitigation way. As this strategy make plant safe even though HPSI and PAFS are both failed, it can effectively enhance the plant safety. For this strategy two RCGVSs and two POSRVs are needed as a depressurization system for bleed operation and only one LPSI is enough for feed operation. H-SIT operation is also needed to make up core inventory during bleed operation. For this operation, four H-SITs have to be used to make up core safely. Based on the risk analysis using PSA method, if this strategy is applied, core damage frequency is 1.868e-6 which declined 7 percent from original model.

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REFERENCES

[1] Arun Kumar Nayak et al, "A review: passive system reliability analysis–accomplishments and unresolved issue," *Frontiers in energy research 2*, (2014): 40.

[2] Kwon, T., & Park, C. "Hybrid SIT for Passive Safety System," *Transactions of the Korean Society Spring* Meeting, KOREA, May 30, 2013.

[3] Park, R. J., & Hong, S. W, "Effect of SAMG entry condition on operator action time for severe accident mitigation," *Nucl. Eng. Des*., 241(5), 1807-1812, (2011).

[4] Sang Hee Kang et al, "Thermal-Hydraulic Analysis for Supporting PSA of SBLOCA in APR+," *Probabilistic Safety Assessment and Management 12*, Honolulu, Hawaii, June22, 2014