An Estimation of the Effectiveness of an Hybrid-SIT System under SGTR Accident

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Abstract: A hybrid safety injection tank (H-SIT) is designed to passively inject coolant into a reactor coolant system under any pressure condition without depressurization, which enables it to be applied in various accident types. In some accident conditions, if long-term cooling is not achievable because required active mitigation components are unavailable, the H-SIT can replace the function of failed components at least for a certain time period. Since the H-SIT has limited inventory, the mitigation strategy needs to be carefully developed to effectively enhance a plant safety. This study focuses on the risk effect of the H-SIT system under steam generator tube rupture (SGTR) accident with safety injection system (SIS) failure, which has been conventionally considered to cause core damage. The use of the H-SIT provides diversity of mitigation options and allows more time to repair the failed components. In order to address plant dynamics in a realistic manner, this study considers the variety of secondary-side cooling performances with corresponding repair probability. Multiple-tube rupture cases are also considered. The analysis results demonstrate that the H-SIT extensively contributes to the plant risk reduction.

Keyword: Hybrid SIT, Passive system, PSA analysis

1 Introduction

In current nuclear power plants (NPPs), most of the safety-critical functions are implemented by active systems. In order to ultimately meet safety goals, however, relying on active systems alone does not seem to be enough. As passive systems provide advantages for mitigating station black out accidents[1] and also contribute to the diversity of mitigation action during accident situations, combining passive and active systems for mitigating accidents has become more important in the nuclear industry[2][3].

A hybrid safety injection tank (H-SIT) was invented to passively inject coolant into a reactor coolant system (RCS) under any pressure condition without depressurization [4]. In low-pressure accidents, such as medium and large-break loss of coolant accidents (LOCA), the H-SIT system injects water using the pressure from nitrogen gas as a conventional safety-injection tank. In high-pressure accidents, it provides inventory make up by gravitational force after the pressure of the H-SIT is equalized with the RCS pressure.

Due to the H-SIT's broad usability, many additional mitigation strategies to enhance plant safety can emerge. There have been previous research on enhancing plant safety by utilizing the H-SIT system [5][6][7] and they suggest that the H-SIT can be used with active mitigation systems for long-term cooling in various accident conditions. Generally, there are three long-term cooling strategies in pressurized water reactors (PWRs): Operation of the shutdown cooling system or residual heat removal system, maintaining secondary cooling systems (SCSs), and feed-and-bleed (F&B) operation [8]. These strategies require successful operation of long-term cooling components; if there are unavailable, some of the strategies may not be applicable. Since functions of the H-SIT are similar to a safety injection pump (SIP), it can be used for safety injection of F&B operation, for core inventory make up to maintain secondary cooling or for core cooling to satisfy shut down cooling entry condition.

According to previous research, PWR accidents can be divided into 8 cases based on the availability of long-term cooling components. Proper long-term cooling strategy in each case can be summarized as in Figure 1 [7]. The accidents that belong to cases 4, 7 and 8 cannot be mitigated by conventional long-term cooling strategies due to unavailability of some long-term cooling components, especially SIPs. In these situations, the novel mitigation strategies utilizing the H-SIT can be adopted to mitigate accidents. In the previous paper, a new F&B operation strategy with the H-SIT and a shutdown cooling pump (SCP) for the case 7 was developed [7].

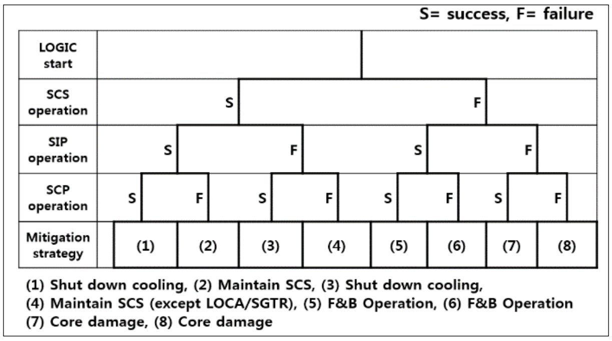


Figure 1 Accident classification based on availability of long-term cooling components

Under LOCA or steam generator tube rupture (SGTR) accident, maintaining the secondary-side cooling does not guarantee the core cooling since LOCA or SGTR causes a void inside the RCS; this void disturbs natural circulation in the RCS. This abnormality surely affects heat transfer to the SCS, and it decreases cooling capability. It is the reason that long-term mitigation strategy of case 4 is limited to non-LOCA accidents. This study focuses on the accident mitigation strategy by utilizing the H-SITs to achieve the long-term cooling under SGTR accidents. SGTR accidents have a special characteristic different from LOCA: Coolant loss is limited by equalizing pressure between the RCS and a steam generator (SG). As the H-SIT can be used for high pressure injection, it can make up the core inventory and remove the void. If the void is eliminated, natural circulation can be secured again and the SCS can successfully remove the residual heat of the core. In case the SCS partially loses its cooling ability, the void has to be larger than normal because pressure equalizing is delayed. Use of the H-SIT can also be applied even in these severe situations due to its sufficient injection capacity. Figure 2 graphically shows the effectiveness of core make up by using the H-SIT.

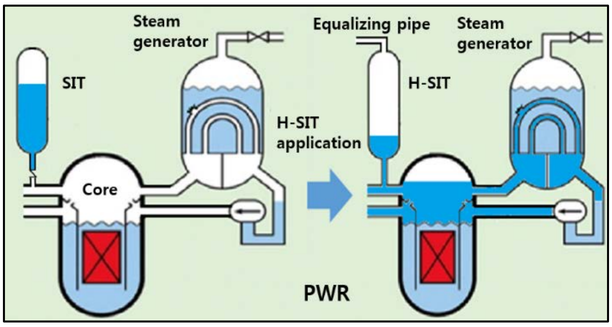


Figure 2 Core make up with H-SIT in SGTR accidents

Conventional probabilistic safety assessment (PSA) analysis considers performance degradation of heat removal system as failure [8], even if degraded ability can contribute to extend the time until core damage and allow higher chance of repair [9]. For realistic analysis, various cooling capacities of the SCS are considered to estimate the effectiveness of the H-SIT. This study suggests an effective mitigation strategy with the H-SIT during SGTR accidents and quantifies the conditional core damage probability (CCDP) in consideration of repair probability, which varies with cooling ability of the SCS. There are two possible scenarios: The H-SIT may facilitate a long-term cooling with partial cooling ability of the SCS, or it can increase repair probability of failed SCS even if it is used just for extending time until core damage. Based on these scenarios, the CCDP is estimated and the effectiveness of mitigation strategy with the H-SIT under SGTR accidents is evaluated.

Based on these features of the H-SIT in SGTR accidents, advantages of the use of Hybrid-SIT under SGTR accidents is analyzed by estimating plant risk using CCDP in this paper..

2. The operation strategy of the H-SIT in SGTR and MSGTR accidents

2.1 Analysis for conventional mitigation strategies of SGTR accidents

When SGTR accidents occur, the most critical factor in deciding on a proper mitigation strategy is whether natural circulation inside the RCS is maintained. If it is not maintained, heat cannot be removed by the SCS. Since efficiency of natural circulation is disturbed by a void generation inside the RCS [10], most conventional NPPs use the safety injection systems (SISs) to mitigate SGTR accidents regardless of the availability of the SCS [11][12]. Figure 3 shows SGTR event tree model of OPR 1000, which is a typical NPP in KOREA [12]. Based on this figure, if all SIPs including high and low pressure injection pumps fail, this sequence is regarded as the same as the core damaged condition.

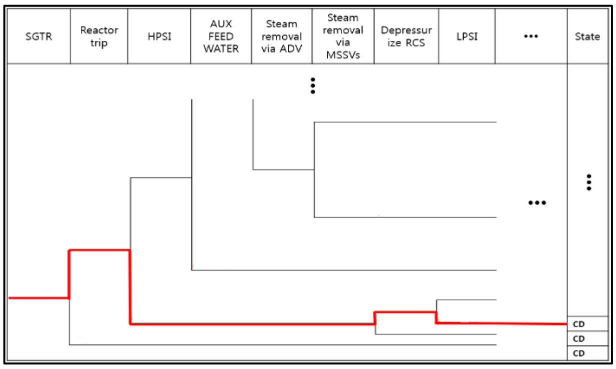


Figure 3 SGTR event tree model of OPR 1000

Some plants, especially the latest plant models such as advanced power reactor plus (APR+), use the SCS to mitigate SGTR accidents even if a void exists in the RCS [8]. This strategy, however, can be applied to only few PWR models. Most conventional PWRs still have difficulty mitigating SGTR accidents using the SCS only. In addition, this strategy is only useful when cooling performance of the SCS is normal. If it is degraded for any reasons, this causes a large amount of void inside the RCS. Therefore, applicability of this strategy to all PWRs still has many restrictions.

From the point of view of plant safety and economy, mitigation of SGTR accidents using the SCS has many advantages compared with using SISs. If the SCS is available, SISs can be a back-up system; it enhances the diversity of mitigation options. Moreover, SISs have a high failure probability because of their design characteristics, which is shown in Figure 4 [7].

All safety injection systems including SIPs and SCPs share a single safety injection line. Common cause failure of V143, V543, and V227 affect the availability of SISs remarkably. For this reason, if SISs are only used for mitigation accidents, they may increase CDF too much. In addition, since use of SCPs entails the depressurization of RCS, contamination of containment area must occur. It results in great economic loss to the plant due to decontamination cost and shutdown for decontamination. Therefore, mitigation of SGTR with the SCS is the best option that an operator can choose.

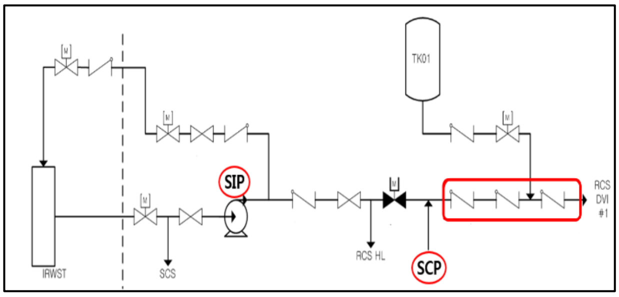
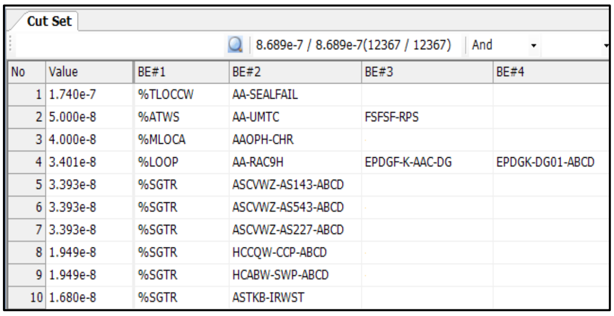


Figure 4 The schematic diagram of SIS configuration

2.2 Comparative analysis of PSA results of mitigation strategies

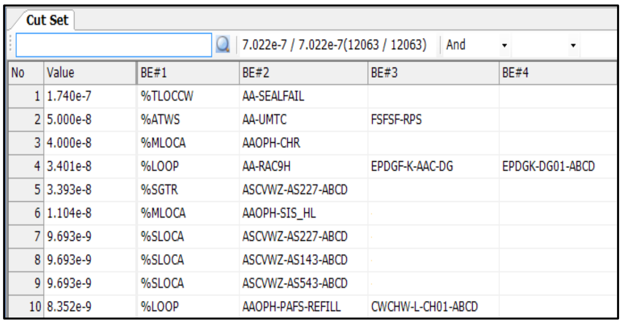
In this section, PSA analysis is performed to determine how much the plant risk operator can reduce when the SCS is used instead of SISs. For this analysis, a PSA input model that is developed from the previous study [7] is used and possible mitigation strategies of SGTR are referred from the references [8][12]. APR+ is selected as a representative PWR model because the H-SIT was initially planned to be integrated into the APR+. Based on the results from the PSA analysis, if the SCS is not used for long-term cooling, CDF is 8.689e-7. Figure 5 shows the detailed information of analysis results. Six out of the top 10 cutsets that have the highest portion of the CDF, are related with SGTR, and most of them include a common cause failure of valves in the safety injection systems.



No	Value	BE#1	BE#2	BE#3	BE#4
1	1.740e-7	%TLOCCW	AA-SEALFAIL		
2	5.000e-8	%ATWS	AA-UMTC	FSFSF-RPS	
3	4.000e-8	%MLOCA	AAOPH-CHR		
4	3.401e-8	%LOOP	AA-RAC9H	EPDGF-K-AAC-DG	EPDGK-DG01-ABCD
5	3.393e-8	%SGTR	ASCVWZ-AS143-ABCD		
6	3.393e-8	%SGTR	ASCVWZ-AS543-ABCD		
7	3.393e-8	%SGTR	ASCVWZ-AS227-ABCD		
8	1.949e-8	%SGTR	HCCQW-CCP-ABCD		
9	1.949e-8	%SGTR	HCABW-SWP-ABCD		
10	1.680e-8	%SGTR	ASTKB-IRWST		

Figure 5 PSA results when SISs are used for mitigation of SGTR

While the SCS is used for long-term cooling, CDF can be dropped to 7.022e-7, which is shown in Figure 6. Five cutsets that associate with SGTR accidents are disappeared and CDF decreases 19% compared with the results in Figure 5. Based on those results, using the SCS for a long-term cooling strategy remarkably increases the plant safety.



No	Value	BE#1	BE#2	BE#3	BE#4
1	1.740e-7	%TLOCCW	AA-SEALFAIL		
2	5.000e-8	%ATWS	AA-UMTC	FSFSF-RPS	
3	4.000e-8	%MLOCA	AAOPH-CHR		
4	3.401e-8	%LOOP	AA-RAC9H	EPDGF-K-AAC-DG	EPDGK-DG01-ABCD
5	3.393e-8	%SGTR	ASCVWZ-AS227-ABCD		
6	1.104e-8	%MLOCA	AAOPH-SIS_HL		
7	9.693e-9	%SLOCA	ASCVWZ-AS227-ABCD		
8	9.693e-9	%SLOCA	ASCVWZ-AS143-ABCD		
9	9.693e-9	%SLOCA	ASCVWZ-AS543-ABCD		
10	8.352e-9	%LOOP	AAOPH-PAFS-REFILL	CWCHW-L-CH01-ABCD	

Figure 6 PSA result when secondary cooling systems is only used for mitigation of SGTR

2.3 Effect of PAFS cooling performance degradation

As mentioned in section 2.1, the mitigation strategy using the SCS can be only available if cooling performance of the SCS is normal even in APR+. In order to assess applicability of this strategy, the performance degradation effect should be estimated first. For this estimation, thermal-hydraulic (TH) analysis is performed, and MARS ver. 1.3 is used as a reference TH code [13], and input model of APR+ is developed.

In APR+, a passive auxiliary cooling system (PAFS) is integrated as the SCS. Based on the system analysis, there are two reasons to degrade cooling performance of the PAFS: PAFS operation valve open failure and the main steam safety valve (MSSV) stuck open problem. Since the PAFS consists of many valves, the unavailability of this system depends heavily on the failure of the valves. Among those valves, an operation valve has the highest failure probability because it consistently operates during accidents. If it does not open perfectly, the cooling rate is obviously lower than normal value due to a lower flow rate inside of the PAFS. The flow rate of passive cooling systems has close relation to heal removal rate. Figure 7 shows the TH analysis results when the operation valve has 5% of its full area. According to these results, core exit temperature (CET) rapidly increases up to the acceptance criteria of cladding failure, which is 1477K [14], even if the designed cooling ability of the PAFS is high enough to cool down the core [15].

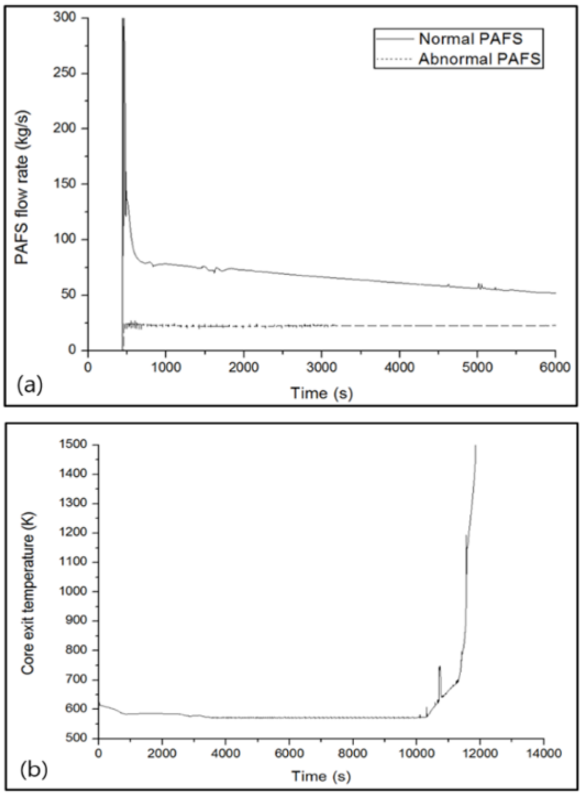


Figure 7 The PAFS flow rate and (b) the CET when operation valve of the PAFS has 5% of its full area

The MSSV stuck open problem is another reason to degrade performance of the PAFS [16] because it deteriorates the efficiency of natural circulation inside the PAFS. Performance of natural circulation of passive cooling system is remarkably important for its cooling ability. Figure 8 shows the TH analysis results when one MSSV is fully opened and stuck at the same time. According to analysis results, mass flow rate of the PAFS is very unstable, and it finally reaches zero when the coolant inside the PAFS is all dried out. CET rapidly increases up to cladding failure criteria. Therefore, mitigation of SGTR accidents using the SCS is impossible even in APR+ when cooling performance of the SCS is degraded.

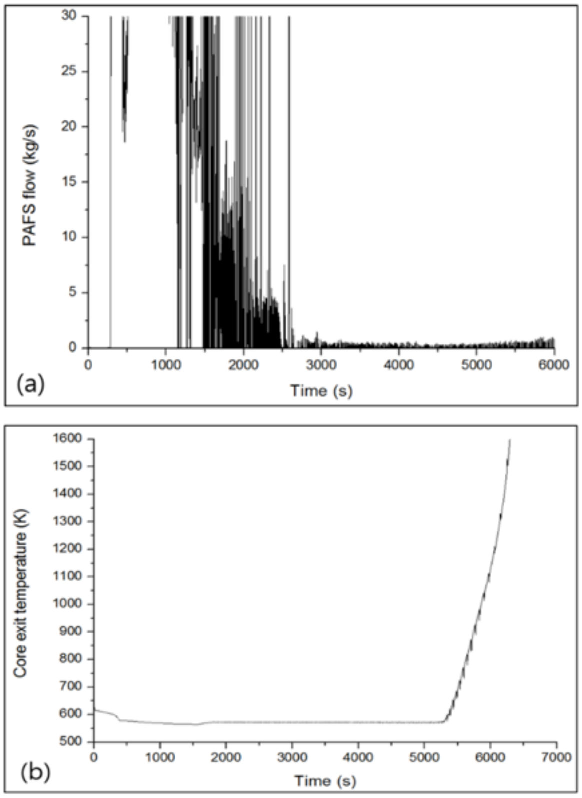


Figure 8 (a) The PAFS flow rate and (b) CET when a MSSV is stuck opened

2.4 MSGTR accidents with cooling performance degradation of the PAFS

MSGTR is an accident in which multiple tubes are ruptured for the same reasons. According to risk analyses of PWRs, the risk of MSGTR event is known to be larger than that of a single SGTR event even though the probability of SGTR occurrence is larger than that of the MSGTR event [17][18]. In addition, since the SG consists of more than 5,000 heat transfer tubes, multiple tube rupture accidents cannot be ignored. For these reasons, MSGTR accidents are considered in this study. According to the nuclear regulatory commission (NRC) report, up to 2-5 ruptured tubes should be reasonable for MSGTR accidents modeling [19]. In this study, a case of 5 ruptured tubes is selected for the conservative analysis.

Based on the TH analysis results, when the PAFS operation valve has 5% of its full area and SISs fail, the CET under MSGTRs reaches the cladding failure criteria earlier than SGTRs. In general, leakage rate through the ruptured part of SG tube mainly depends on the size of the area at the beginning of the accident. The lager break area causes higher leakage rate due to its high flow capacity. The SG is completely filled by transferred coolant in MSGTR, and this coolant leaks out through the MSSV as water, not as steam. After pressure between the RCS and the SG is almost equalized, flow rate through the ruptured part mainly depends on the amount of pressure difference between the RCS and the SG because the amount of flow caused by a small pressure difference can be covered by the flow capacity of the small break area. Figure 9 (a) shows these phenomena. Integrated flow rate in MSGTR is faster at the first moment, while it is similar at the last moment of the accident. In consideration of those two reasons, core inventory is dried out earlier in MSGTR accidents.

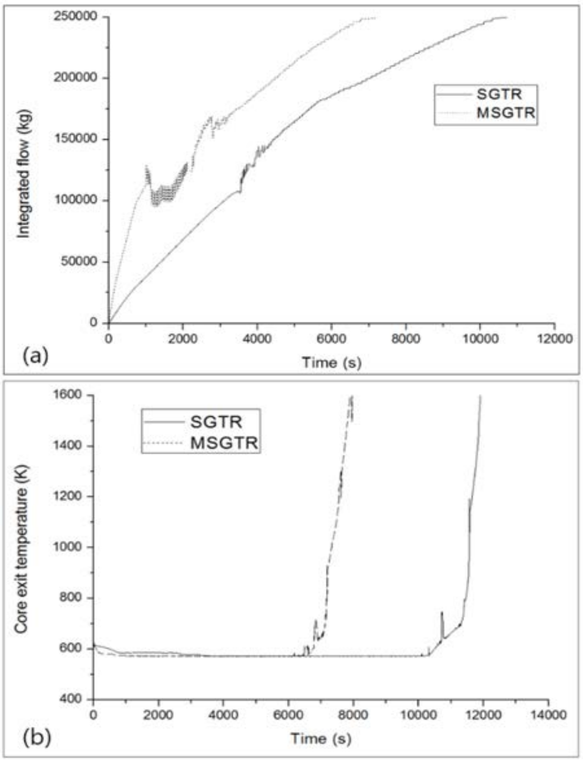


Figure 9 Comparative results of (a) the integrated flow from the core and (b) CET between SGTR and MSGTR when operation valve fails

When an MSSV of one SG in which tubes are not ruptured is stuck open, cladding failure times of SGTR and MSGTR are almost similar. This similarity occurs because the RCS is over-cooled due to a large amount of coolant release through an MSSV. This large amount of coolant rapidly removes the SG pressure and causes over-cooling of the RCS. For this reason, pressure between the RCS and the SG is equalized much earlier; a full level of the SG is prevented even in MSGTR. If it is prevented, coolant that is leaked from the RCS is just accumulated inside the SG. It is not leaked to the outside as a form of water. After pressure between the RCS and the SG is almost equalized, the coolant inside of the SG starts to move back to the core by gravity. That is the reason why integrated flow rates and CET are similar in both accidents, as shown in Figure 10.

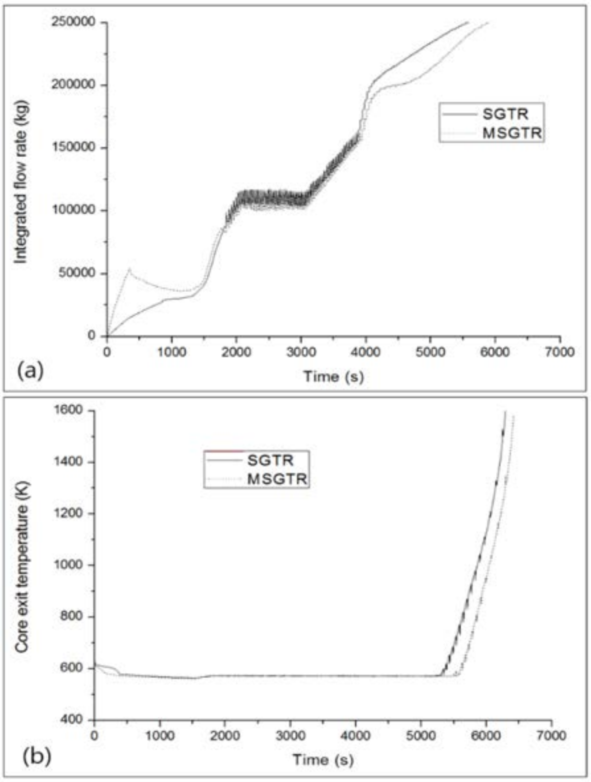


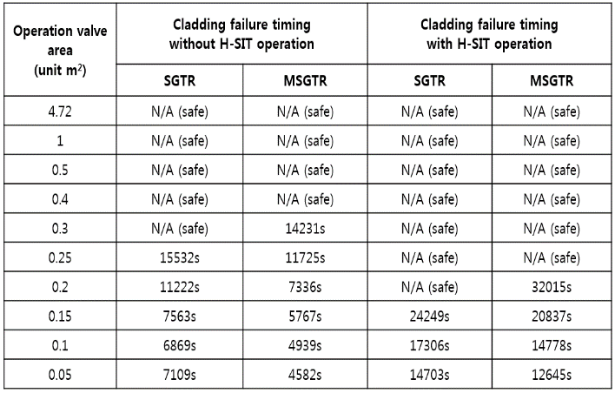
Figure 10 Comparative results of (a) the integrated flow from the core and (b) the CET between SGTR and MSGTR when the MSSV is stuck open

2.5 The mitigation of SGTR and MSGTR accidents with the H-SIT system

In section 2.1, utilization of the SCS to mitigate SGTR is defined as the best strategy to enhance plant safety effectively. As aforementioned, however, this mitigation strategy cannot be generally applied to PWRs due to a void inside the RCS. Since the H-SIT is the safety injection system, which can inject the coolant into the RCS in any pressure condition, the void can be removed by high-pressure injection using the H-SIT. It helps not only to maintain natural circulation but also to maintain long-term cooling operation. Therefore, mitigation of SGTR using the SCS is applicable to all PWRs when the H-SIT system is integrated. This system can also be effectively used when a cooling ability of the SCS is degraded because of its sufficient injection capacity. These are the main ideas for a mitigation strategy using the SCS and the H-SITs. In this strategy, it is assumed that the H-SITs start to operate at 1800s after accidents occur because operators usually need 30 min to confirm whether this accident is SGTR. In APR+, there are four H-SITs and all H-SITs inject coolant at the same time for rapid inventory make up. After RCS inventory is made up, operators can use the PAFS to cool down the core.

The cooling performance of the PAFS is degraded not only when the operation valve fails but also when the MSSV is stuck open. As their degrees of failure are very various, an acceptable number of accident cases are considered according to the size of the open area. Cooling performance of each size is reflected to estimate cladding failure time using TH simulation code. In the case of the PAFS operation valve failure accident, accident cases are divided into 10 cases from the area of $4.72m^2$, which is the maximum area of operation valve, and cladding failure time is evaluated in each case. Table 1 shows the cladding failure timing according to open areas of operation valve.

Table 1 The cladding failure timing according to open areas of the operation valve

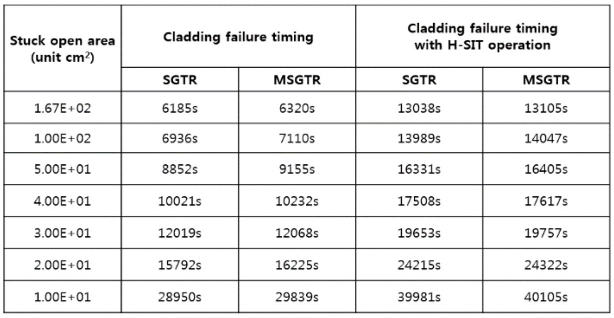


Operation valve area (unit m^2)	Cladding failure timing without H-SIT operation		Cladding failure timing with H-SIT operation	
	SGTR	MSGTR	SGTR	MSGTR
4.72	N/A (safe)	N/A (safe)	N/A (safe)	N/A (safe)
1	N/A (safe)	N/A (safe)	N/A (safe)	N/A (safe)
0.5	N/A (safe)	N/A (safe)	N/A (safe)	N/A (safe)
0.4	N/A (safe)	N/A (safe)	N/A (safe)	N/A (safe)
0.3	N/A (safe)	14231s	N/A (safe)	N/A (safe)
0.25	15532s	11725s	N/A (safe)	N/A (safe)
0.2	11222s	7336s	N/A (safe)	32015s
0.15	7563s	5767s	24249s	20837s
0.1	6869s	4939s	17306s	14778s
0.05	7109s	4582s	14703s	12645s

If the area of the PAFS operation valve is less than $0.25m^2$ in SGTR, natural circulation inside the RCS cannot be maintained because the void inside the RCS is too large. If the H-SIT is used for inventory make-up, the valve area that can make long-term cooling possible is extended to $0.15m^2$. If an operation valve area is lower than $0.15m^2$, utilization of the H-SIT can extend the time until cladding damage. In these situations, operators have the additional time to recover the operation valve or to use other mitigation systems. In the case of MSGTR accident, natural circulation can be maintained until 0.25 m^2 of operation valve with the H-SIT. Cladding damaged times of MSGTR are generally shorter than in the single tube rupture cases because of a large initial leak of coolant through an MSSV.

In this section, accident cases are divided into 7 cases and there is no case in which SGTR accidents are mitigated forever because the SG eventually dries out due to continuous loss of inventory through an MSSV. In this situation, as the PAFS has the function to cool the water that comes from SG, the PAFS also totally loses its cooling ability. For this reason, the effectiveness of H-SIT operation should be relatively lower than in the operation valve failure cases. Nevertheless, operators can have the additional time to recover the PAFS or to use other mitigation systems with the H-SIT system because it can extend time until cladding failure. Table 2 shows the cladding failure timing according to opening areas of the MSSV.

Table 2 The cladding failure timing according to open areas of the MSSVs



Stuck open area (unit cm^2)	Cladding failure timing		Cladding failure timing with H-SIT operation	
	SGTR	MSGTR	SGTR	MSGTR
1.67E+02	6185s	6320s	13038s	13105s
1.00E+02	6936s	7110s	13989s	14047s
5.00E+01	8852s	9155s	16331s	16405s
4.00E+01	10021s	10232s	17508s	17617s
3.00E+01	12019s	12068s	19653s	19757s
2.00E+01	15792s	16225s	24215s	24322s
1.00E+01	28950s	29839s	39981s	40105s

According to results, the cladding failure timings in MSGTR accidents are later than in SGTR accidents. The main reason for this tendency is the higher back flow rate from the SG to the RCS. As mentioned in section 2.4, at the beginning of SGTR and MSGTR accidents, lots of coolant is accumulated inside of the SG. After pressure is equalized, accumulated coolant starts to move back to the core again. At this time, a back flow rate of MSGTR is higher than that of SGTR due to its large break area. For this reason, a total amount of coolant leakage from the core is relatively low in the case of the MSGTR.

3. The estimation of conditional core damage probability in consideration of repair probability

Utilization of the H-SIT system can mitigate SGTR and MSGTR accidents for a long time or extend the cladding failure time effectively. If accidents are perfectly mitigated using the H-SIT, a core damage probability (CDP) absolutely reaches to zero because accidents are not linked to core damage anymore. If the H-SIT extends the time until core damage, the CDP has to be estimated in consideration of repair probability because secured additional time until core damage can be used for recovering failed components. Since success of repair means the core is not damaged, the CDP is defined as 1 - repair probability in this study.

3.1 Allowable time estimation for the PAFS repair

In order to assess the repair probability, allowable time for recovery of failed components should be evaluated first. In this section, natural circulation stop timing of RCS is suggested instead of cladding failure time as the allowable time to realistically estimate repair probability. In general, if natural circulation stops, the PAFS cannot be used for cooling the RCS even if its cooling ability is recovered because residual heat generated from the core cannot be transferred to the SG. Therefore, natural circulation stop timing is regarded as the allowable time for PAFS repair in this study. While, in steady states, u-tubes of the SG are fully filled with the water, the void inside u-tubes starts to generate when SGTR occurs. If a void is larger, water inside the u-tubes is totally disconnected in the end. At this moment, natural circulation inside RCS is stopped. In this study, this timing is considered natural circulation stop timing.

Natural circulation stop timing is estimated by using the same conditions used in section 2.5, and those are tabulated in Table 3 and 4. The tendency of those results is similar to the results in Table 1 and 2 for the same reasons. Based on the results, natural circulation stops from 0.2m^2 of the operation valve area with H-SIT operation in SGTR. In MSGTR, natural circulation stops from 0.25m^2 of the operation valve area with H-SIT operation. In addition, even if long-term cooling is impossible using the H-SIT, natural circulation is additionally maintained up to 13427s at 0.25m^2 of the valve area in SGTR and 18516s at 0.2m^2 of the valve area in MSGTR. If the valve area decreases, natural circulation stop timing also decreases. If the operation valve area is below 0.05m^2 in MSGTR, H-SIT operation has no benefits because natural circulation already stops before H-SIT operation, which is 1800s after the accident occurs. In case of the MSSV stuck open failure, while H-SIT operation cannot secure long-term cooling operation, H-SIT operation extends natural circulation timing up to 7800s at 10cm^2 of the area of an MSSV in SGTR and 8832s at 10cm^2 of the area of an MSSV in MSGTR. In these cases, if the valve area increases, natural circulation stop timing decreases.

Table 3 The natural circulation stop timing according to open areas of the operation valve

Operation valve area (unit m^2)	Natural circulation stop timing without H-SIT operation		Natural circulation stop timing with H-SIT operation	
	SGTR	MSGTR	SGTR	MSGTR
4.72	N/A (safe)	N/A (safe)	N/A (safe)	N/A (safe)
1	N/A (safe)	N/A (safe)	N/A (safe)	N/A (safe)
0.5	N/A (safe)	N/A (safe)	N/A (safe)	N/A (safe)
0.4	N/A (safe)	N/A (safe)	N/A (safe)	N/A (safe)
0.3	N/A (safe)	7142s	N/A (safe)	N/A (safe)
0.25	7556s	5053s	N/A (safe)	N/A (safe)
0.2	5035s	2488s	N/A (safe)	21004s
0.15	3602s	2542s	17029s	13303s
0.1	3002s	2107s	10841s	8588s
0.05	2867s	1709s	8184s	1709s

Table 4 The natural circulation stop timing according to open areas of the MSSVs

Stuck open area (unit cm^2)	Natural circulation stop timing		Natural circulation stop timing with H-SIT operation	
	SGTR	MSGTR	SGTR	MSGTR
1.67E+02	2054s	2136s	7310s	7238s
1.00E+02	3978s	4022s	7950s	7834s
5.00E+01	5435s	5560s	10188s	10349s
4.00E+01	6526s	6622s	11598s	11734s
3.00E+01	8096s	8167s	13919s	13849s
2.00E+01	11418s	11577s	18125s	18459s
1.00E+01	23459s	23761s	31259s	32593s

3.2 The estimation of the conditional core damage probability with the H-SIT system

PAFS cooling ability can be degraded by failure of valves, such as the PAFS operation valve and the MSSV. According to the NUREG 3154, the valve components in NPP can be averagely recovered in 5.2 hours [20]. That means, even if the H-SIT cannot make long-term cooling, it can effectively increase the repair probability of the PAFS. In this study, repair probabilities can be estimated using repair times that are referred from the NUREG 3154 and allowable times for repair that are estimated in section 3.1. The principle of the calculation is that the valve repair is considered a success if the mean time to repair (MTTR) of the failed valve is less than the representative allowable time (T_A); P (MTTR < T_A) is the repair probability of the valve. If T_A increases due to operation of the H-SIT, repair probability also increases. Figure 11 shows the conceptual illustration for estimating repair probability.

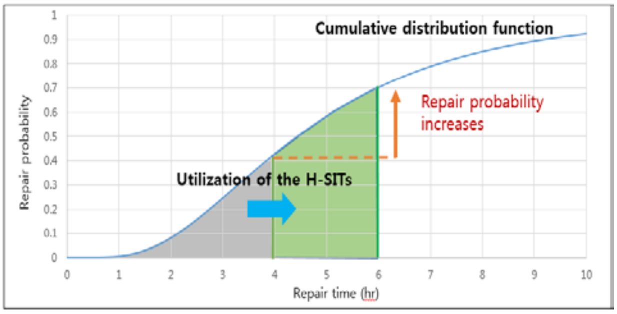


Figure 11 Conceptual illustration for estimating repair probability

In the NUREG 3154, repair times, which are empirical data for all types of valves in all nuclear plant systems, are gathered into the in plant reliability data system, and lognormal distribution parameters are developed based on those empirical data. Generally, lognormal distribution has expectation and variance as shown below: (E(X) = expectation, V(X) = variance, μ = expectation of normal distribution, σ = standard deviation of normal distribution)

$$\mathrm{E(X)} = e^{\mu+\sigma^2/2} \tag{1}$$

$$\mathrm{V(X)} = e^{2\mu+\sigma^2}\left(e^{\sigma^2}-1\right) \tag{2}$$

Expectation and the standard deviation of the normal distribution can be determined by using equations, which are presented above. If expectation and the standard deviation of the normal distribution are determined, the repair probability can be determined using normal-curve area calculation (F(x)), and Table 5 shows the parameters of the lognormal distribution of repair times of the valve components:

$$F(X) = \emptyset \left(\frac{\ln(x) - \mu}{\sigma} \right) \tag{3}$$

Table 5 Statistic information of valve repair times in NPP [20]

Parameter	In plant reliability data system information
Number of observations	2809
Mean time	5.2 h
Median time	4.0 h
Mode time	2.0 h
Standard deviation	3.2 h
Maximum repair time	880 h
Minimum repair time	0.5 h

Repair probabilities of valves are evaluated to estimate the amount of risk reduction. Since the core is damaged when recovery of the PAFS fails under condition defined in this study, 1 – repair probability of the PAFS can be regarded the same as factor of the CCDP. For this calculation, it is also assumed that if the PAFS is recovered within the allowable time, long-term cooling is surely secured.

Based on the results, which are shown in Figure 12, H-SIT operation remarkably decreases the CCDP. Specifically, the CCDP reaches to zero until 0.2m^2 of the operation valve area in SGTR and until 0.25 m^2 in MSGTR because long-term cooling is secured using the H-SIT. If the valve area is 0.2 m^2 in SGTR, the H-SIT operation has the biggest effect on the plant safety, and it decreases the risk from 0.9793 to 0. If the valve area is 0.25 m^2 in MSGTR, the H-SIT operation decreases the CCDP from 0.9788 to 0. Even if long-term cooling is not secured, the CCDPs decrease from 12% to 54% in SGTR accidents and from 13% to 68% in MSGTR accidents because extended natural circulation stop timing enhances the recovery of the PAFS. If the valve area is below 0.05m^2 in MSGTR, H-SIT operation hardly affects the repair of the PAFS because natural circulation is stopped before H-SIT operation starts.

In case MSSV is stuck open, H-SIT operation cannot make the CCDP factors zero. As MSSV stuck open accidents cause depletion of the coolant inside the PAFS regardless of H-SIT operation, core damage certainly occurs. It, however, effectively decreases the risks from 8% to 31% in SGTRs and 8% to 32% in MSGTRs because natural circulation stop timings are extended. These results are shown in Figure 13. In conclusion, operation of the H-SIT is useful to enhance the availability of the SCS and it decreases plant risk effectively.

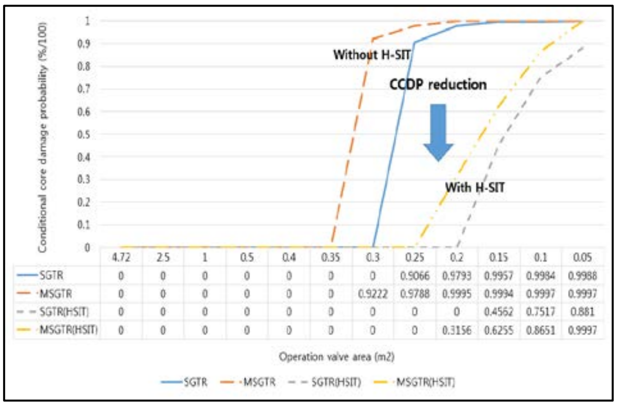


Figure 12 CCDP change according to areas of the operation valve

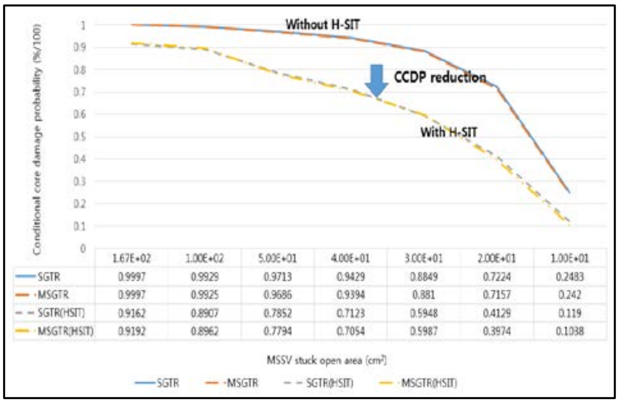


Figure 13 CCDP change according to stuck open areas of the MSSV

4. Conclusion

In SGTR accidents, whether the PAFS can make a long-term cooling is very critical to reduce the plant risk. In order to use the PAFS, maintenance of a natural circulation inside RCS has to be guaranteed to transfer the heat from the core to the PAFS. If SGTR or MSGTR accident occurs, however, the void inside RCS is inevitably generated due to loss of coolant, and it disturbs the natural circulation. In addition, if the SCS partially loses its ability, it causes a bigger amount of void inside RCS because pressure equalizing is delayed. Therefore, core inventory should be made up using SISs to secure natural circulation in SGTR accidents.

Based on the PSA analysis result, if cooling by the PAFS without SIS injection is possible in SGTR, CDF can be decreased up to 19% in comparison of mitigation strategy, which uses SISs. For this reason, the mitigation strategy of SGTR using the H-SIT and the PAFS is suggested, and effectiveness of strategy is estimated. To evaluate this effectiveness, cladding failure time and natural circulation stop timing is firstly estimated using the TH simulation code. Based on the natural circulation stop timing and empirical data, repair probabilities are also estimated.

Based on the analysis results, if the H-SIT is integrated, the CCDP remarkably decreases under conditions of the PAFS operation valve failure. Especially, from full area to $0.2m^2$ in SGTR and from full area to $0.25m^2$ in MSGTR, the CCDPs reach to the zero because long-term cooling operation is secured by using the H-SIT. Even if long-term cooling is not secured, the CCDPs also decrease from 12% to 54% in SGTR accidents and from 13% to 68% in MSGTR accidents because natural circulation stop timings are extended. In these cases, H-SIT operation maximally extends natural circulation stop timing up to 13427s in SGTR and 18516s in MSGTR. Therefore, abnormal PAFS can be additionally recovered during this extended time. In case MSSV is stuck open, H-SIT operation cannot make the CCDPs zero because the SG eventually dries out due to continuous loss of inventory through the MSSV. It, however, effectively decreases the CCDPs from 8% to 31% in SGTR and 8% to 32% in MSGTR. Natural circulation stop timing is maximally extended up to 7800s in SGTR and 8832s in MSGTR accident.

All things considered, operation of the H-SIT is useful to enhance the availability of the SCS in valve failure conditions; thus it effectively decreases the plant risk. In addition, application of the H-SIT makes long-term cooling possible to PWRs using only SCSs. Therefore, use of the H-SIT is highly recommended in SGTR and MSGTR accidents in order to enhance the diversity of mitigation strategies and increase the accident mitigation coverage using SCSs in the PWRs.

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