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Original Article

DEVELOPMENT OF AN OPERATION STRATEGY FOR A HYBRID SAFETY INJECTION TANK WITH AN ACTIVE SYSTEM

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ABSTRACT

A hybrid safety injection tank (H-SIT) can enhance the capability of an advanced power reactor plus (APR+) during a station black out (SBO) that is accompanied by a severe accident. It may a useful alternative to an electric motor. The operations strategy of the H-SIT has to be investigated to achieve maximum utilization of its function. In this study, the master logic diagram (i.e., an analysis for identifying the differences between an H-SIT and a safety injection pump) and an accident case classification were used to determine the parameters of the H-SIT operation. The conditions that require the use of an H-SIT were determined using a decision-making process. The proper timing for using an H-SIT was also analyzed by using the Multi-dimensional Analysis of Reactor Safety (MARS) 1.3 code (Korea Atomic Energy Research Institute, Daejeon, South Korea). The operation strategy analysis indicates that a H-SIT can mitigate five types of failure: (1) failure of the safety injection pump, (2) failure of the passive auxiliary feedwater system, (3) failure of the depressurization system, (4) failure of the shutdown cooling pump (SCP), and (5) failure of the recirculation system. The results of the MARS code demonstrate that the time allowed for recovery can be extended when using an H-SIT, compared with the same situation in which an H-SIT is not used. Based on the results, the use of an H-SIT is recommended, especially after the pilot-operated safety relief valve (POSRV) is opened.

1. Introduction

The Fukushima accident was not managed properly because of a lack of mitigation systems and strategies against a long-term station black out (SBO) [1]. The application of passive features has been suggested for properly mitigating another severe accident because passive systems do not require external energy supplies and passive safety features can increase the diversity of mitigation techniques [2,3]. For this reason, passive safety features have become an important issue in the nuclear field, and a substantial number of studies related to passive safety have been performed [4–6].

A conventional nuclear power plant (NPP) is primarily composed of active systems; thus, conventional operating

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procedures focus on the operation of active systems. When a passive safety system is added to a NPP, a new operation procedure is needed for the effective use of the passive system alongside the active system. This process is essential to enhance the safety of NPPs. However, only a few studies in the nuclear field have addressed the operation strategies of passive systems. Therefore, the operation strategy for a passive system should be studied further.

A previous study suggested the principle of a hybrid safety injection tank (H-SIT) system to enhance the ability of accident mitigation [7]. Many researchers have worked on H-SIT systems for the development of passive safety. In brief, the H-SIT is a new design concept for a passive safety injection system. The H-SIT system can inject water by using the pressure from nitrogen gas as a normal SIT in low-pressure accidents such as a large-break loss-of-coolant accident (LOCA). The H-SIT system can also inject water by using gravitational force in over-pressure accidents such as a SBO. The term “over-pressure” means that the pressure inside a reactor vessel is higher than the injection pressure of the safety injection pump (SIP). In over-pressure accident scenarios, the SIP cannot inject water because the SIP shut-off head has a limitation. The H-SIT is the only system that can inject water without depressurization in over-pressure accidents. Thus, this function of the H-SIT is critical. To drive the H-SIT in an over-pressure scenario, the battery-driven isolation valves open, and the pressure of the H-SIT is then balanced with the pressure of the reactor coolant system (RCS) through the pressure-equalizing pipe. This pipe is situated between the H-SIT and the pressurizer (PZR). The process for driving the H-SIT can be conducted in any pressure range, which includes the over-pressure situation. Thus, when the pressure is balanced, the emergency core cooling water can be injected by using the gravitational force in all scenarios such as the over-pressure scenario. Fig. 1 presents the outline of the H-SIT system.

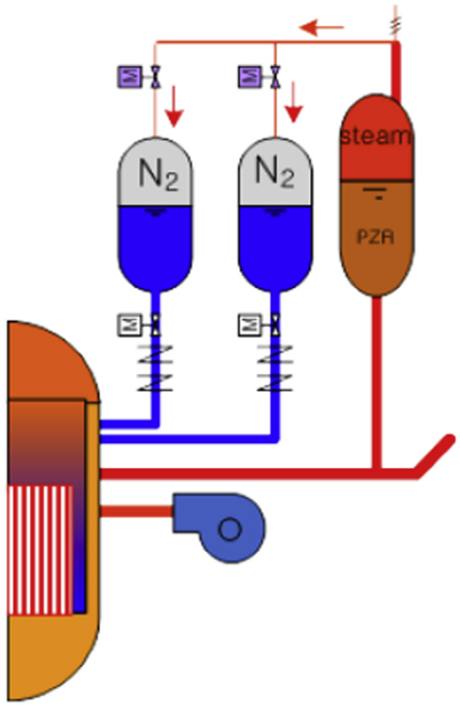

Fig. 1 – Outline of the hybrid safety injection tank system [7]. N2, nitrogen; PZR, pressurizer.

A H-SIT can be used with an active injection system to increase the diversity of the safety system. A H-SIT is also planned to adjust to the advanced power reactor plus (APR+). Therefore, developing an H-SIT operation strategy is a suitable example of establishing the parallel operation of passive and active systems. Hence, this study focused on developing a methodology for constructing an operations strategy of an H-SIT, and using it to construct an actual operations strategy. In section 2, several technical methods are presented for the development of scenarios in which an H-SIT is suitable. In section 3, a timing effect analysis is performed for the specific scenarios that were determined in section 2. The scenario was analyzed using the thermal-hydraulic code and by calculating the recovery probability. This study suggests an effective strategy for the operation of an H-SIT in a conventional NPP and explains how that strategy is developed logically.

2. Scenario development

The H-SIT is primarily used in over-pressure accidents, which occur when many abnormal conditions coincide. Thus, these accidents are complicated to analyze. In this accident situation, the H-SIT can be also used with many active systems; therefore, parallel operation between an H-SIT and active systems should be considered for an operation strategy. Active systems can be used for accident mitigation instead of an H-SIT. This suggests that an H-SIT is not applicable to all accident scenarios. Therefore, applicable scenarios in which H-SIT needs to be used should first be developed. The complexity of making an operation strategy for accidents decreases if applicable scenarios are developed.

2.1. *Hybrid safety injection tank functions and parameters*

In this section, parameters are determined to develop applicable scenarios efficiently. Parameters are an important standard to use to reasonably select applicable scenarios from among all possible accident scenarios. They also help in analyzing the characteristics and phenomena of complicated accidents.

In this study, the parameters were determined by considering three key points: (1) the plant state, (2) the characteristics and functions of the H-SIT, and (3) the soundness of the safety systems that are associated with the H-SIT operation. In an accident situation, the functions of the H-SIT are duplicated by many active systems. Therefore, whether the active systems that are related with H-SIT functions are sound is a very critical point for constructing the operation strategy of an H-SIT.

The H-SIT was originally designed for the inventory makeup of the RCS. This function can be used for various purposes such as pressure control or heat removal. Before developing

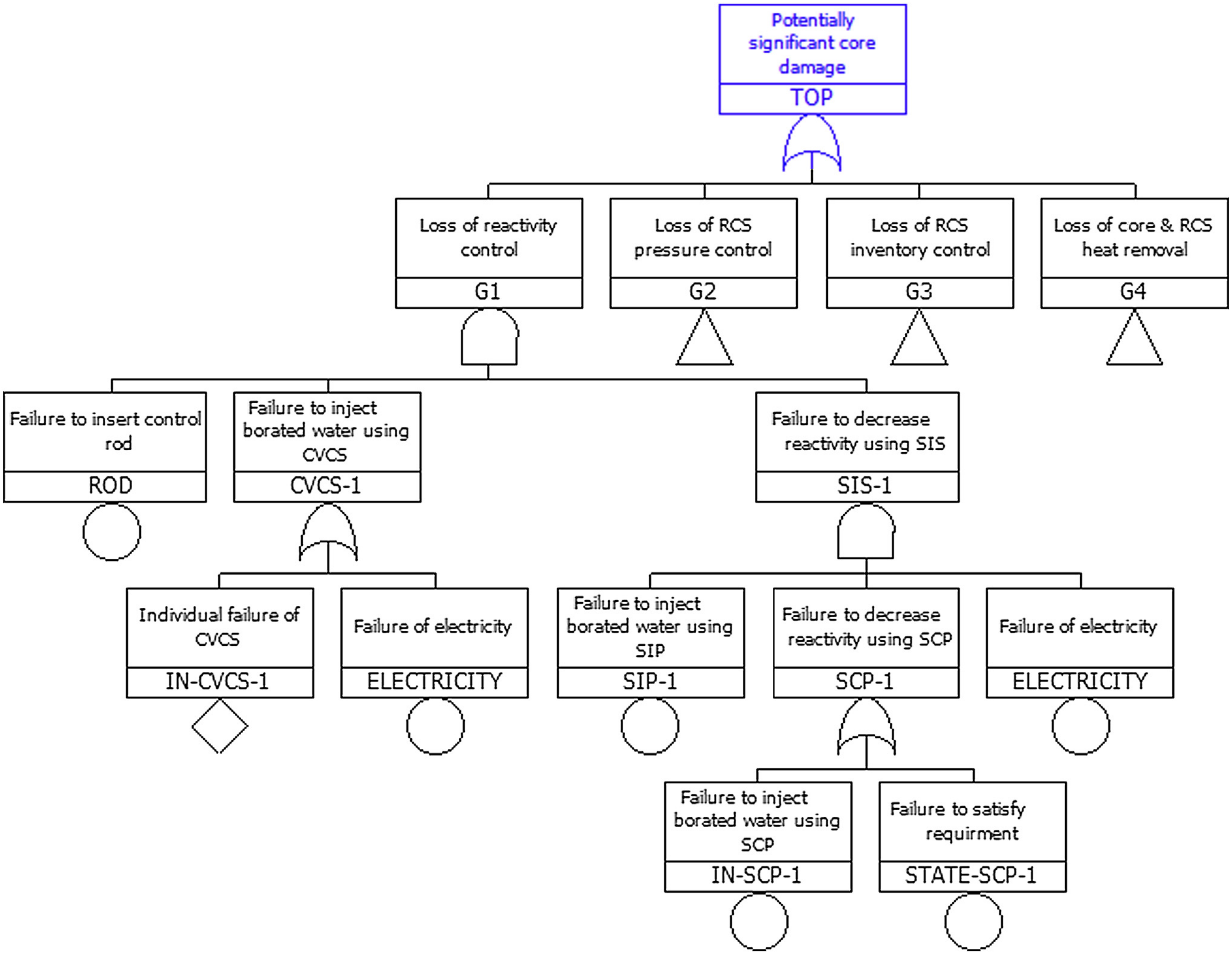

Fig. 2 – A portion of the developed master logic diagram for the target plant. CVCS-1, chemical and volume control system; RCS, reactor coolant system; SCP-1, shutdown cooling pump; SIP, safety injection pump; SIS, safety injection system.

an operation strategy, all possible functions of the H-SIT should be identified. In this study, we used the master logic diagram (MLD) technique for this purpose. The MLD technique starts with a top event—which is defined as an undesired event—and proceeds to decompose the top event into simpler contributing events [8]. If specific contributing events are determined, the safety functions that are required for a mitigating event are also determined. Core damage is the top event of the MLD because preventing core damage is the main purpose of the safety injection system. Based on emergency operating guidelines and technical papers [9,10], safety functions that prevent core damage are identified and modeled in the MLD, as Fig. 2 shows.

The following four functions of the H-SIT were obtained from this MLD analysis: (1) RCS inventory control; (2) RCS pressure control; (3) core heat removal when secondary cooling is sound; and (4) feed-and-bleed operation. The four functions obtained through the MLD technique are used for finding the proper safety systems related to H-SIT operations. For the RCS inventory control, the safety injection system and the safety injection tank have to be considered as the safety systems, based on technical papers [10,12]. For the RCS pressure control, the safety depressurization system and chemical and volume control system (which function as the safety injection and pressurizer spray system) have to be considered. For core heat removal, the safety injection system, forced circulation cooling system, natural circulation cooling system, and shutdown cooling system have to be considered. For feed-and-bleed operations, the safety injection system and forced circulation cooling system have to be considered [11,12]. These are all safety systems related to an H-SIT operation.

Based on the analysis for safety systems, an active safety injection system (SIS) is associated with all functions of an H-SIT. The operation of an H-SIT is closely correlated with the operation of a SIS. The H-SIT was originally designed as an injection system; thus, most H-SIT functions can be duplicated by an active SIS [13]. These two systems can be described as having a functional parallel relationship. Thus, these two systems can be substituted for each other. Despite the functional parallel relationship, this substitution is unacceptable for all scenarios because of the different principles of operation between the H-SIT and the active SIS. Thus, differences between the H-SIT and active SIS should be identified to

Table 1 – Differences between the safety injection pump, hybrid safety injection tank, and conventional safety injection tank.

Differences	Contents
Electricity	✓ Electricity is required for the SIP operation. ✓ H-SIT and conventional SIT do not require electricity.
Operating pressure	✓ SIP and conventional SIT have a pressure limit for injecting water. ✓ H-SIT can inject water at any pressure.
Method of operation	✓ SIP can inject water directly to the RCS without the operation of other support systems that use electric power. ✓ H-SIT requires several other systems such as an equilibrium valve and pipe. In addition, an H-SIT injects water by using gravitational force. ✓ SIT can inject water directly to the RCS without the operation of other support systems. It is already pressurized by nitrogen gas and it uses check valves.
Long-term cooling	✓ Recirculation using a SIP can provide long-term cooling of the RCS. ✓ The H-SIT and SIT have a limited tank inventory. Thus, long-term cooling is impossible.

H-SIT, hybrid safety injection tank; RCS, reactor coolant system; SIP, safety injection pump; SIT, safety injection tank.

distinguish conditions in which the operation of an H-SIT cannot be replaced by an active SIS. Under this condition, the H-SIT should be preferentially used.

An analysis for identifying the differences between the H-SIT, conventional SIT, and SIP is performed by comparing their unique characteristics and the characteristics of passive and active systems [14]. This information is presented in Table 1. The differences between these three systems have to be considered for determining the parameters because these differences are used to find scenarios in which H-SIT should be used instead of an active SIS.

Table 2 presents the parameters for identifying scenarios for which the H-SIT can be used, based on many considerations. The parameters primarily verify the soundness of the safety systems and the plant states. The costs of mitigation actions resulting from radioactive contamination and heat removal efficiency from the primary side to the secondary side are also considered when determining the parameters.

This study considered a shutdown cooling pump (SCP) as a backup low-pressure injection system. The SCP has mechanical properties similar to the low-pressure injection pump; however, it is only used for long-term cooling in a conventional operation strategy because the nuclear field considers using one system for multiple purposes is unsafe. However, the new version of the emergency operating guidelines for the APR1400 [9] indicates that a SCP can be used for low-pressure injection in an urgent accident situation because this procedure can enhance the diversity of safety systems.

An H-SIT system can inject water during low-pressure accidents. This function is also used with a conventional SIT that has well-developed operation procedures by the Engineered Safety Features Actuation System signal. Thus, the operation procedures of an H-SIT during low-pressure conditions are not a target of this study.

2.2. *Classification of the accident cases*

Accidents in NPPs can be divided into two categories: single-failure accidents and multiple-failure accidents. A single-failure accident is characterized by a single event such as a LOCA or steam generator tube rupture. A multiple-failure accident is characterized by two or more events. Multiple-failure accidents have not been considered a common issue in the past. However, after the Fukushima accident, many individuals believe that multiple failures may occur during natural disasters.

The Probabilistic Safety Assessment (PSA) conducting report selects several single events as the initiating event [11]. These initiating events, except for SBO, are not considered scenarios for the operation of an H-SIT because it has the

Table 2 – Parameters for a hybrid safety injection tank operation strategy.

Standard		Parameter	
Soundness of the SIP	When the SIP fails	Availability of the SCP for safety injection	
Differences between SIP and H-SIT	Electricity	Soundness of the electricity	
	Operating pressure	Pressure of the RCS	
		Soundness of the SG	
		Soundness of depressurization system	
		If depressurization is possible	Radioactive contamination of containment
		Temperature difference between the primary and secondary sides (for the efficiency of heat removal through the SG)	
	Operating method	LOCA point	
	Long-term cooling	Availability of the SCP for long-term cooling	
		Maintain the PAFS	
		Recirculation	

H-SIT, hybrid safety injection tank; LOCA, loss-of-coolant accident; PAFS, passive auxiliary feedwater system; RCS, reactor coolant system; SCP, shutdown cooling pump; SG, steam generator; SIP, safety injection pump.

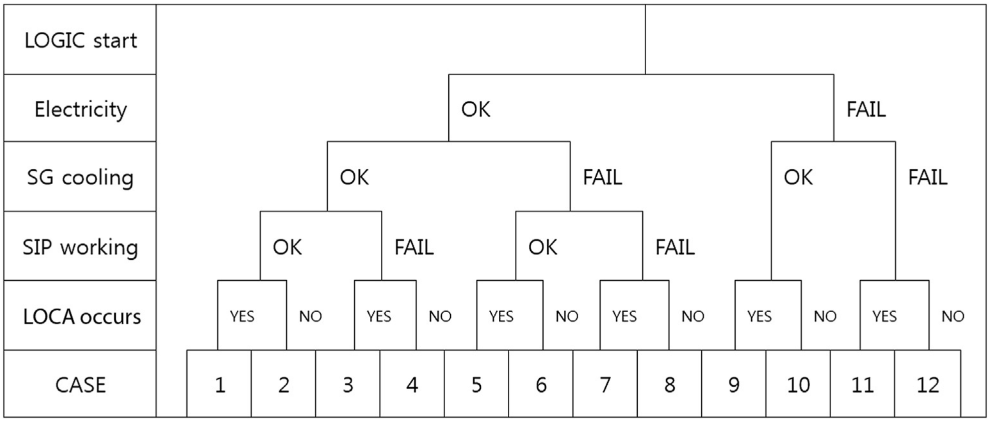

Fig. 3 – Classification of the accident cases. LOCA, loss-of-coolant accident; SG, steam generator; SIP, safety injection pump.

special function of injecting water during over-pressure accidents for which a SIP cannot inject water. When an initiating event occurs, an SIP and passive auxiliary feedwater system (PAFS) are supposed to be sufficient [11]. Thus, a SIP can be used after the pressure is decreased below the SIP shut-off head using the PAFS in single events [15]. Therefore, an H-SIT must be retained for an unexpected over-pressure scenario that is caused by multiple accidents. Thus, H-SIT systems are typically used during multiple-failure accidents.

Several scenarios exist for multiple-failure accidents in an NPP. An operating procedure cannot be developed for each of these scenarios. This study classifies all scenarios into a few cases for the development of an effective operation procedure. The operation procedure is developed on a case-by-case basis.

Clear standards are required to classify scenarios. The soundness of the SIP is a very important standard for classifying scenarios because the H-SIT and SIP have a functionally parallel relationship. The function of the H-SIT can be replaced with the function of the SIP. In addition, the SIP operation typically has a higher priority for injecting water, compared with the H-SIT operation, because the SIP can inject coolant without regard to water inventory. The H-SIT should be used for high-pressure accidents caused by unexpected situations. Therefore, whether the SIP can work is critical when an operator decides to operate the H-SIT. In addition, an H-SIT uses gravitational force to inject water. Therefore, it cannot be used simultaneously with an active injection system such as an SIP because an active pump causes a pressure difference in the RCS. Using gravitational force to inject water is difficult if a pressure difference occurs in the RCS [16]. Thus, the SIP operation has a large effect on the operating procedure of the H-SIT.

The purpose of the operating procedure for the H-SIT is to mitigate accidents. To achieve effective mitigation, accidents must be clearly understood in terms of their phenomena and their impact on the plant. Therefore, to construct an optimal operating procedure, several accidents with phenomena that cannot be easily distinguished are considered as one case, and accidents that have a similar effect on the steam supply system are considered as one case. To establish these cases, this study refers to the following three standards from the emergency operating guidelines: (1) whether electricity is available; (2) whether a steam generator is available; and (3) whether a LOCA occurs [9].

The four standards for classifying accidents are the following: (1) the availability of electricity, (2) the soundness of the steam generator (SG) cooling system (e.g., the PAFS), (3) the occurrence of LOCA, and (4) the soundness of the SIP. Fig. 3 presents the classification logic. These four classification criteria yield 12 accident cases. This study assumes that cases 9, 10, 11, and 12 are not target cases for developing the operating procedure of an H-SIT with an active system because active systems cannot work in these cases. Therefore, cases 9–12 do not require a procedure for parallel operation.

2.3. *Reorganization of parameters*

In the previous, section, all parameters used to develop applicable scenarios were determined and then the accident cases were classified. The parameters presented in Table 2 are generally used to identify the scenarios for all cases of multiple accidents. Not all parameters were used to develop the operating procedure of the H-SIT for any particular accident case because not all of them are relevant to every case. Thus, the parameters that are needed for developing scenarios in each case should be distinguished. The parameters were therefore reorganized to find the proper parameters for developing applicable scenarios in each case.

In section 2.2, the cases were divided by specific standards. Therefore, different cases have different conditions. Thus, to find appropriate parameters for each case, the parameters were also reorganized by using the same standards as the case. The reorganization process is described in Table 3. This process is used to match the conditions with the proper parameters. If operators know the conditions of the accident case, then they automatically know the parameters that they have to check by using this process.

2.4. *The decision process for the applicable conditions of H-SIT operation*

The H-SIT uses gravitational force to inject water after pressure between the pressurizer and RCS is equalized in an

Table 3 – Parameters reorganized, based on the accident conditions.

Conditions		Parameters
All		RCS pressure Long-term cooling (recirculation) Availability of depressurization
SG	Working	When the pressure is higher than the SIP operating pressure, check the efficiency of the heat removal through the SG Maintain the PAFS Availability of the SCP for long-term cooling Radioactive contamination
	Not working	Radioactive contamination
SIP	Working	–
	Not working	Availability of the SCP for low-pressure injection
LOCA	Occurs	LOCA point
	Does not occur	–

LOCA, loss-of-coolant accident; PAFS, passive auxiliary feedwater system; RCS, reactor coolant system; SCP, shutdown cooling pump; SG, steam generator; SIP, safety injection pump.

over-pressure accident. The operation of an active pump causes a pressure difference in the RCS, which makes water injection using gravitational force difficult. Therefore, an H-SIT cannot be used simultaneously with an active injection system such as a SIP [16]. For this reason, the operation strategy of an H-SIT with an active system should focus on prioritization between the H-SIT and active injection systems. A decision process is therefore needed.

For the decision process, parameters were determined by using the reorganized table in section 2.3. This process determines which system between the H-SIT and active injection systems should be used in a specific accident condition. Therefore, the conditions that necessitate the use of the H-SIT can surely be determined by the decision process. Those conditions can be interpreted as an applicable scenario of H-SIT operation. This process is performed for every case to identify applicable scenarios. The decision process for the applicable scenarios of the H-SIT operation is described in Tables 4 and 5. These decision processes are made by using the information of cases 3 and 5 as examples.

2.5. *The development of scenarios for which the H-SIT should be used*

An important characteristic of the H-SIT is that it cannot be used for long-term cooling because it has a limited amount of water. The H-SIT can only be used for temporary mitigation. Thus, the H-SIT is primarily used to extend the allowed time for the recovery of the components that have failed, rather than to mitigate accidents perfectly.

The decision process suggests there are 14 scenarios in which the H-SIT should be used in an accident scenario. The scenarios are listed in Table 6.

According to the analysis, the use of the H-SIT is required to extend the allowed time for the recovery from five failures: SIP failure, PAFS failure, depressurization system failure, SCP failure, and recirculation system failure. When these failures occur, the use of the H-SIT is first compared with the use of the other active systems. If the recovery fails during the extended allowed time for recovery using the H-SIT, then the other active systems can be used. This is the basic operation strategy of an H-SIT with active systems.

The results of the decision process also demonstrate that each scenario has its own pressure range in which the H-SIT can be used. The pressure ranges are listed below. There are four pressure ranges for the H-SIT: (1) SIP maximum injection pressure–Pressure Safety Valve (PSV) open pressure; (2) shutdown pressure–PSV open pressure; (3) maximum SCP operating pressure–PSV open pressure; (4) maximum SCP operating pressure–shutdown pressure.

3. Timing effect analysis

3.1. *The set of conditions*

Each scenario has proper pressure ranges in which the H-SIT must be used. Thus, the injection time of the H-SIT also has a range because it can be used at any time if the RCS pressure is within the proper range. The efficiency of the H-SIT can change, depending on the time until use. In this section, a timing effect analysis will be performed to determine the best time to use the H-SIT.

The H-SIT was modeled by using the thermal-hydraulic code MARS KS ver. 1.3. The reference plant model is an APR+. The code inputs of the APR+ and H-SIT were provided by Korea Hydro and Nuclear Power Co., Ltd. (KHNP).

In this study, the allowed time for the recovery extension of the depressurization system is a target function of the H-SIT. The valves are easily fixed, compared with other components such as the SIP pump. Thus, the extension of the allowed time for recovery *via* using the H-SIT has a considerable effect when the valve fails. Two pressure ranges are selected for this analysis: (1) SIP maximum injection pressure–PSV open pressure and (2) shutdown pressure–PSV open pressure.

In accidents within pressure range 1, a small-break LOCA occurs, the SIP is sound, and the SG and depressurization system fails. These are the same conditions as in case 5 of the classification. A change in the PZR pressure in this condition is

Table 4 – Process for determining the conditions that are applicable to the hybrid safety injection tank operation (Case 3).

Parameters		Conditions and decisions							
SCP for long-term cooling		Possible	Impossible						
Maintain PAFS		N/A	Possible		Impossible				
RCS pressure		N/A	Maximum SCP operating pressure–Shutdown pressure		Maximum SCP operating pressure–PSV open pressure				
Depressurization		Do not need	Do not need		Possible			Impossible	
SCP for low-pressure injection		Usable	Usable	Unusable	Usable		Unusable	Usable	Unusable
Efficiency of heat removal		N/A	N/A (Does not need depressurization)		H-SIT is superior to SCP		N/A (No injection system)	N/A (Cannot depressurize)	
Radioactive contamination									
Recirculation cooling		N/A	N/A (Does not need depressurization)		Possible	Impossible	N/A (Cannot depressurize)		
System selection	H-SIT	Do not use	Do not use	Use	Use first	Use	Use	Use	Use
	SIP	Does not need recovery	Does not need recovery	Recovery	Does not need recovery		Recovery	Does not need recovery	Recovery
	SCP	Conditional use	Conditional use	Recovery	Conditional use	Cannot use	Recovery	Cannot use	Recovery

H-SIT, hybrid safety injection tank; N/A, not applicable; PAFS, passive auxiliary feedwater system; RCS, reactor coolant system; SCP, shutdown cooling pump; SG, steam generator; SIP, safety injection pump.

illustrated in Fig. 4. This study assumes that the break size is 0.01 ft^2.

After a shutdown, the pressure decreases rapidly because of the trip and the LOCA. The SIP injection signal then occurs. When the main steam safety valve is open, the decay heat is removed from the SG; thus, the RCS temperature remains nearly constant until the SG dries out. For this reason, the pressure of the RCS remains constant until the SG dries out. After the SG dries out, the pressure of the RCS starts to increase because the RCS loses its heat sink. The SIP will not work once the RCS pressure exceeds the SIP's maximum injection pressure. In this scenario, no water can be injected into the RCS if the depressurization system is not recovered. The code finally stops at approximately 6300 seconds because of cladding failure caused by a peak cladding temperature exceeding 1477 K. Usually fuel cladding fails if the cladding temperature exceeds 1477 K [17]. If the cladding has failed, a substantial amount of radiation must be released through the break. Thus, technicians can no longer fix failed components. Therefore, the allowed time for recovery is defined as the time between the occurrence of an accident and the occurrence of the cladding failure.

The SIP can be used when the RCS pressure is below the SIP's maximum injection pressure (12.47 MPa). Therefore, an H-SIT would typically used after the RCS pressure exceeded 12.47 MPa in this scenario. Two operation times for the H-SIT were selected based on the availability of the safety system and the change in the PZR pressure. These times occur when the RCS pressure exceeds the SIP's maximum injection pressure and the pilot-operated safety relief valve's (POSRV's) open time.

In accidents within range 2, a small-break LOCA occurs and the SIP, SG, and depressurization system fail. A change in the PZR pressure is illustrated in Fig. 5. These conditions are the same as those in case 7 of the classification. This study also assumes that the break size is 0.01 ft^2.

This pressure change is similar to that in case 1. However, damage to the core occurs more rapidly in case 2 than in case 1 because the SIP is not functional in this scenario. The calculation is stopped at approximately 3500 seconds because of the high cladding temperature, as in case 1.

In this case, four operation times of the H-SIT are selected, based on the trends in the PZR pressure. These times are (1) the fastest operable time, (2) the main steam safety valve open time, (3) the SG dry out time, and (4) the POSRV open time. This study assumes that the operator requires 5 minutes to use the H-SIT after shutdown. Therefore, the fastest operable time is 300 seconds.

3.2. *Results of the timing analysis for the H-SIT*

The use of the H-SIT can extend the allowed time for the recovery of the depressurization system. If the depressurization system is recovered, the SIP can be operated with depressurization. Therefore, the function of the H-SIT is required in this scenario. A change in the PZR pressure depends on the operation timing of the H-SIT, as depicted in Fig. 6.

Table 7 illustrates that if the H-SIT is used, the allowed time for the recovery of the depressurization system can be extended by up to 11,224 seconds, compared with when the

Table 5 – Process for determining the conditions that are applicable to the hybrid safety injection tank operation (Case 5).

Parameters		Conditions and decisions			
RCS pressure		SIT operating pressure–Maximum SIP operating pressure	Maximum SIP operating pressure–PSV open pressure		
Depressurization		N/A	Possible		Impossible
Recirculation cooling		N/A	Possible	Impossible	N/A
Radioactive contamination		N/A	H-SIT is superior to SIP		N/A
System selection	H-SIT	Do not use	Use	Use	Use
	SIP	Use	Conditional Use	Cannot Use	Cannot Use

H-SIT, hybrid safety injection tank; N/A, not applicable; RCS, reactor coolant system; PSV, pressure safety valve; SIP, safety injection pump; SIT, safety injection tank.

Table 6 – Scenarios for which the hybrid safety injection tank should be used.

Case	Applicable scenarios
Cases 1 and 2	If the PAFS maintains a failure status, the H-SIT is used to extend the repair time of the PAFS. If recirculation is impossible, depressurization is also impossible. Hence, the H-SIT is used to extend the repair time of the recirculation system. If depressurization is impossible, the H-SIT is used to extend the repair time of the depressurization system.
Cases 3 and 4	If the SCP fails, no water can be injected into the primary side. Thus, the H-SIT is used to extend the repair time of the SIP or SCP. If PAFS maintains a fail status, the H-SIT is used to extend the repair time of the PAFS. If depressurization is impossible, the H-SIT is used to extend the repair time of the depressurization system. If recirculation is impossible, depressurization is also impossible. Thus, the H-SIT is used to extend the repair time of the recirculation system.
Cases 5 and 6	If the SG fails, the H-SIT is used to extend the repair time of the SG before starting the F&B operation. If depressurization is impossible, the H-SIT is used to extend the repair time of the depressurization system. If recirculation is impossible, depressurization is also impossible. Thus, the H-SIT is used to extend the repair time of the recirculation system.
Cases 7 and 8	If the SG fails, the H-SIT is used to extend the repair time of the SG before starting the F&B operation. If the SCP fails, no water can be injected into the primary side. Thus, the H-SIT is used to extend the repair time of the SIP or SCP. If depressurization is impossible, the H-SIT is used to extend the repair time of the depressurization system. If recirculation is impossible, depressurization is also impossible. Thus, the H-SIT is used to extend the repair time of the recirculation system.

F&B, feed-and-bleed; H-SIT, hybrid safety injection tank; PAFS, passive auxiliary feedwater system; RCS, reactor coolant system; SCP, shutdown cooling pump; SG, steam generator; SIP, safety injection pump.

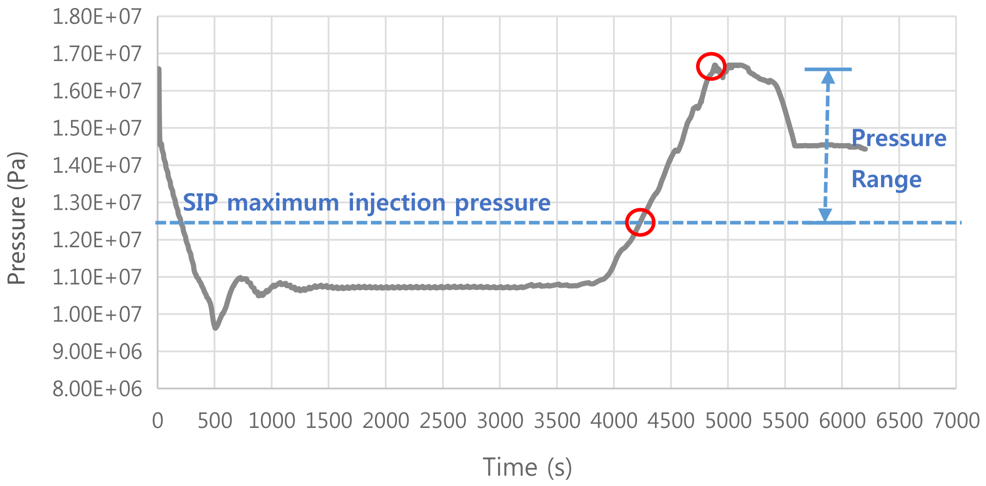

Fig. 4 – Pressurizer pressure during a transient in case 1 without hybrid safety injection tank operation. SIP, safety injection pump.

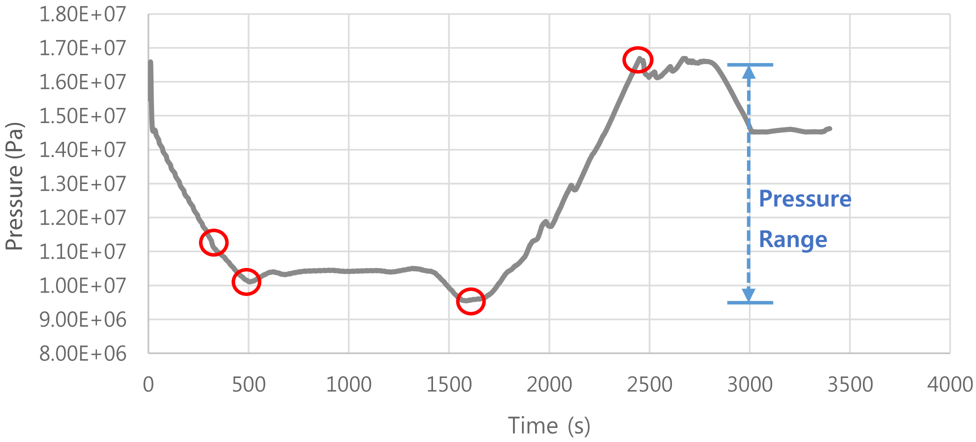

Fig. 5 – Pressurizer pressure during a transient in case 2 without hybrid safety injection tank operation.

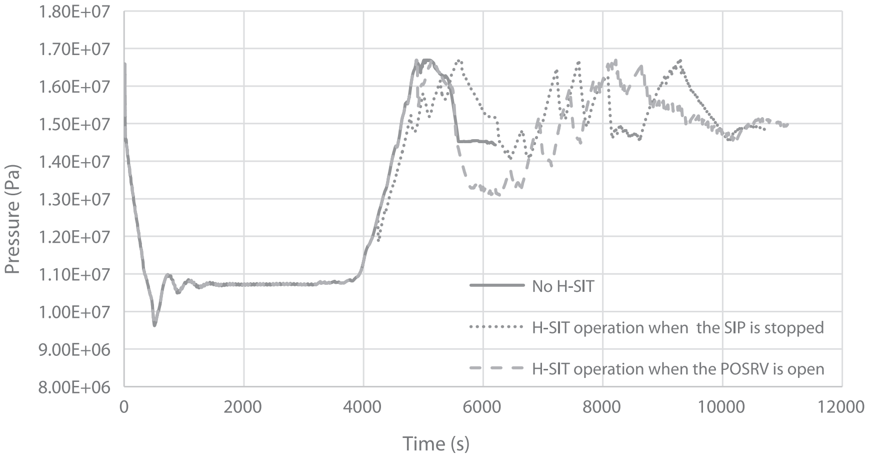

Fig. 6 – Pressurizer pressure during a transient in case 1 for various hybrid safety injection tank initiation times. H-SIT, hybrid safety injection tank; POSRV, pilot-operated safety; SIP, safety injection pump.

H-SIT is not used. If the H-SIT is used after the POSRV opens, the efficiency of the H-SIT is higher than when the H-SIT is used immediately. Therefore, the H-SIT should be used after the POSRV opens.

The use of the H-SIT can also extend the allowed time for the recovery of the depressurization system in case 2. When the SIP is fixed, the SIP cannot inject water if the depressurization system is not recovered because of the RCS pressure. The H-SIT can also be used to extend the allowed time for the recovery of the depressurization system under this condition. The change in the PZR pressure is based on the time required to use the H-SIT, as depicted in Fig. 7.

Table 8 shows that if the H-SIT is used, the allowed time for the recovery of the depressurization system can be extended by up to 8353 seconds, compared with when the H-SIT is not used. The efficiency of the H-SIT when used after the POSRV opens is the best case among the four cases. Thus, the H-SIT should be used after the POSRV opens.

Table 7 – Efficiency of the hybrid safety injection tank, based on the operation timing in case 1.

H-SIT operation timing	Allowed time for recovery (extension rate)
No H-SIT	6302 sec (0.0%)
H-SIT operation when the SIP is stopped	10,861 sec (72.3%)
H-SIT operation when the POSRV is open	11,224 sec (78.1%)

H-SIT, hybrid safety injection tank; POSRV, pilot-operated safety relief valve; SIP, safety injection pump.

3.3. *The change in the recovery probability*

The change in the recovery probability is a suitable criterion for measuring the effect of extending the allowed time for recovery by operating the H-SIT. This change is closely correlated with plant safety. The change in the recovery probability is calculated to determine the effect of the H-SIT in an accident scenario.

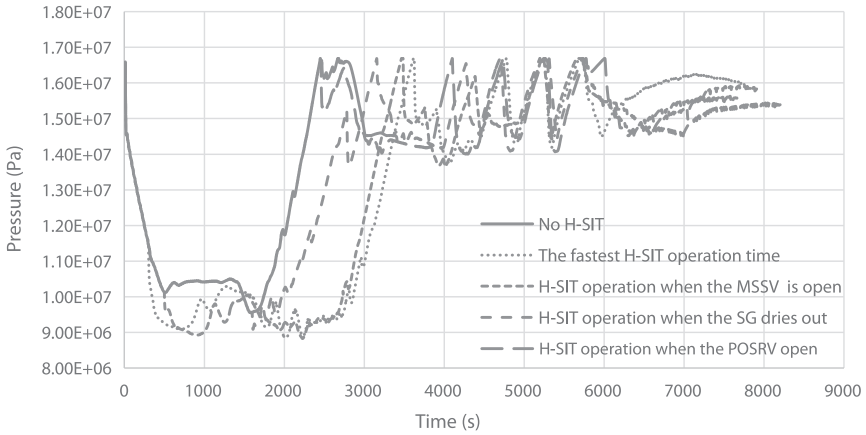

Fig. 7 – Pressurizer pressure during the transient in case 2 for various hybrid safety injection tank initiating times. H-SIT, hybrid safety injection tank; MSSV, main steam safety valve; POSRV, pilot-operated safety; SG, steam generator.

A failed valve typically has a mean time to repair (MTTR). The MTTR varies, depending on the accident condition, valve type, and MTTR distribution. Therefore, an assumption is used when calculating the change in the recovery probability. One assumption is that the MTTR has a log-normal distribution. Detailed information for the log-normal distributions of all types of valves is provided in Table 9 [18]. The previous section recommended using the H-SIT after the open time of the POSRV. Therefore, another assumption in this calculation is the use of 11,224 seconds and 8353 seconds as the representative allowed times for recovery (T_A) for case 1 and case 2, respectively.

Table 8 – Efficiency of the hybrid safety injection tank based on the operation timing in case 2.

H-SIT operation timing	Allowed time for recovery (extension rate)
No H-SIT	3503 sec (0.0%)
The fastest H-SIT operation time	7975 sec (127.7%)
H-SIT operation when the MSSV is open	7808 sec (122.8%)
H-SIT operation when the SG dries out	8043 sec (129.6%)
H-SIT operation when the POSRV is open	8353 sec (138.4%)

H-SIT, hybrid safety injection tank; MSSV, main steam safety valve; POSRV, pilot-operated safety relief valve; RCS, reactor coolant system; SG, steam generator.

Table 9 – In-plant reliability data system parameters for the log-normal distribution of the repair times [18].

Parameter	IPRDS 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

IPRDS, in-plant reliability data system.

The principle of the calculation is that the valve recovery is considered a "success" if the MTTR of the failed valve is less than the representative allowable time. Thus, p (MTTR < T_A) is the probability of the valve recovery. In general, a log-normal distribution has the expectation and variance as shown below in which (E(X) is the expectation, V(X) is the variance, μ is the expectation of normal distribution, and σ is the standard deviation of normal distribution).

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

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

The expectation and the standard deviation of the normal distribution can be determined by using the aforementioned equations. If the expectation and the standard deviation of the normal distribution are determined, then the repair probability can be determined using cumulative distribution function (F(x)):

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

Table 10 shows that if the H-SIT is used, the repair probability increases from 5.1% to 26.8%. Table 11 illustrates that the

Table 10 – The change in the repair probability calculation for case 1.

Case 1	Allowed time for recovery	Repair probability
No H-SIT	6302 sec	5.1%
With H-SIT	11,224 sec	26.8%

H-SIT, hybrid safety injection tank.

Table 11 – The change in the repair probability calculation for case 2.

Case 2	Allowed time for recovery	Repair probability
No H-SIT	3503 sec	0.39%
With H-SIT	8353 sec	12.7%

H-SIT, hybrid safety injection tank.

repair probability increases from 0.39% to 12.7%, if the H-SIT is used. Thus, the use of the H-SIT is an effective method for repairing the depressurization valve. This repair probability is increased further if the H-SIT is used after the POSRV opens.

The repair probability of a depressurization system is not very high in multiple accident cases because these accident cases assume very severe conditions. By contrast, this study used many conservative parameters. This study nevertheless shows that using the H-SIT is an effective way to improve plant safety.

4. Conclusion

An optimum operation strategy for an H-SIT with an active system was analyzed in this paper. The results of this analysis demonstrate that the use of the H-SIT is primarily required to extend the allowed time for the recovery from five failures: SIP failure, PAFS failure, depressurization system failure, SCP failure, and recirculation system failure. These results also demonstrated that each scenario has its own pressure range that requires the use of the H-SIT. Thus, the available injection time of the H-SIT has a range because each scenario has a pressure range. The efficiency of the H-SIT can change, based on the time to use. Therefore, a sensitivity study was performed using the thermal-hydraulic code MARS KS ver. 1.3 to find the optimal operation time of the H-SIT. Two pressure ranges were selected for the sensitivity analysis. The code result of case 1 demonstrates that if the H-SIT is used, the allowed time for the recovery of the depressurization system can be extended by up to 11,224 seconds, compared with when the H-SIT is not used. The H-SIT should ideally be used when the POSRV valve opens. This extended allowed time for recovery affects the repair probability. In case 1, the repair probability increases from 5.1% to 26.8% when the H-SIT was used. For case 2, the allowed time for recovery of the depressurization system can be extended by up to 8353 seconds by using the H-SIT, compared with when the H-SIT is not used. In addition, the H-SIT should ideally be used when the POSRV valve opens. The repair probability increased from approximately 0.39% to 12.7% in case 2.

Conflicts of interest

All contributing authors declare no conflicts of interest.

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