Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2015

Analytical study of the Optimum Operation Strategy for an Hybrid-SIT in SBO

In Seop Jeon *, Hyun Gook Kang [a*],
[a]*Nuclear & Quantum Engineering Department, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701*
First author : inseopjeon@kaist.ac.kr
**Corresponding author: hyungook@kaist.ac.kr*

1. Introduction

The Fukushima accident was not be able to be managed properly due to a lack of effective mitigation systems and strategies against a station black out (SBO) accident [1]. The use of passive systems in nuclear power plants (NPP) has been suggested as an alternative to active systems, as passive systems don't require an external energy source and their installation can increase the diversity of NPP accident mitigation strategies [2].

Recently, research for developing passive systems and operation strategies, such as an integrated passive safety system, has been carried out to enhance plant safety in the nuclear field [3, 4, 5]. General passive systems and strategies however have a critical limitation, especially for passive injection systems. As these systems use gravity as their driving force [6], it is difficult to inject coolant in a passive way in a high-pressure condition thus depressurization is needed to inject coolant to reactor coolant system (RCS).

High-pressure passive injection is essential to mitigate SBO accident effectively. Passive auxiliary feedwater system (PAFS) is the primary system which will be used in residual heat removal. Since the PAFS relies on the natural circulation in primary coolant system and steam condensation in water tank, it is designed to be operated even in a SBO accident [7]. If both PAFSs fail, depressurization of the RCS is necessary for low-pressure injection by normal SITs [8]. This strategy however causes loss of RCS inventory which may cause limited natural circulation in the primary coolant system when the PAFSs are restored. In that sense, if RCS inventory can be maintained during core cool down by high-pressure injection, it increases the diversity of mitigation means. Thus, a Hybrid Safety Injection Tank (H-SIT) that can cover not only low-pressure but also high-pressure passive injection was invented.

While an H-SIT is originally planned to be integrated into Advanced Power Reactor Plus (APR+) [9], it can be used for any pressurized water reactor. This system is specialized for the mitigation of high-pressure accidents, such as SBO accidents, as it is passive system that can inject coolant even in high-pressure conditions. 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 RCS pressure through equalizing pipes, thus allowing the H-SITs to inject water by gravitational force. It is assumed that four H-SITs are installed in the target plant. Each has a 2.5in diameter equalizing pipe and operates at around pilot operated safety relief valve (POSRV) open pressure, 160bar. Figure 1 shows conceptual layout of the H-SIT system.

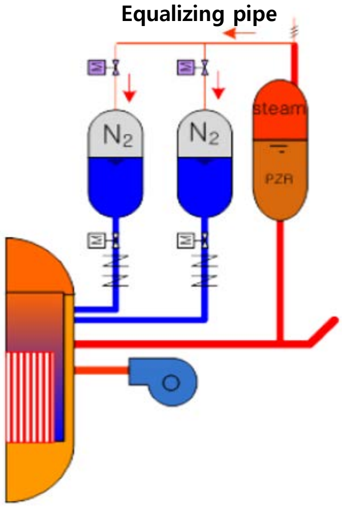

Fig. 1. Outline of an H-SIT system [9]

Restoration of AC power or PAFSs are the only ways to achieve long-term cooling in SBO condition. If AC power is restored, feed and breed operation can be performed using safety injection pump for long-term cooling [10] and if PAFSs are restored, core can be cooled by natural circulation in RCS. The restoration of components, however, takes time. Previous research shows the probability of component restoration changes according to how much available time can be secured [11]. Longer restoration times lead to a high probability of component restoration. Therefore, as H-SITs have a limited inventory, operation of H-SITs have to be supported by the best operation strategy in order to use the inventory effectively for cooling down the core as long as possible.

In the previous study [12], the operation strategy was developed focusing on the mitigation of accidents by combined use of H-SIT and active systems thus it is inappropriate in SBO condition. In this study, we focus on finding a global optimum of H-SIT operation under SBO accident. First the characteristics of the components and accident situations requiring the use of H-SITs are analyzed in detail. Then an analytical study is performed based on the result of characteristic analysis to get the basis of the global optimum point among all possibilities. Based on these analytical optimum points, an analysis using computer code is performed to get more accurate values and to verify the results of the analytical study.

2. Body

An SBO accident is initiated by a total loss of both offsite and onsite AC power. Following this accident, the reactor trips, the main feed water system terminates, and the charging pump stops. When the water level of the steam generator (SG) is lower than the post-trip SG level, the PAFS starts to work. PAFS has enough capacity to cool the reactor core by itself in an accident situation, thus if PAFS works well, H-SIT operation is not needed. The use of H-SIT is needed when PAFSs or the refill of the passive condensation cooling tank (PCCT) for long-term cooling fails. Originally, H-SIT was constructed to prevent the progression of an accident into a severe accident, the probability of which increases dramatically if the core is uncovered. Thus, the purpose of the H-SIT is to protect against the uncovering of the core in order to ensure core safety. In this study, seal LOCA is no longer considered as a phenomenon in SBO because, in APR+, the standstill seal is applied to prevent seal LOCA [14].

2.1 Identification of main factors to develop operation strategy of H-SIT

To develop the operation strategy, in this section, the main factors are identified based on the heat removal equation of H-SIT. The main function of the H-SIT is to remove heat from the reactor core, thus the operation strategy has to be focused on effective heat removal. Hence, we have to express the heat removal process systematically by developing an H-SIT heat removal equation. The equation is expressed based on the following critical principles.

Firstly, to maintain core safety, the amount of heat removal from the core has to be larger than the amount of decay heat generation, as shown in Eq. 1.

$$\int d(t)dt \le \int h_t(t)dt \qquad (1)$$

d(t) = Amount of decay heat generation in unit time.
h_t(t) = Amount of heat removal in the core in unit time.

The change of decay heat generation can be easily calculated given only the time [15]. The amount of heat removal from the core also continuously changes over time, however this amount change is related with many other variables. Thus Eq. 2 is derived to express the heat removal phenomena clearly. Based on the Eq. 2, we know that three critical time variables exist to calculate the heat removal amount from the core. These are coolant injection mass rate from H-SIT, temperature of H-SIT, and evaporation mass rate in the core.

$$h_t(t) = m_i(t)\times C_p\times(T_v - T_{sit}(t)) + m_e(t)\times\mu_{fg} \qquad (2)$$

$m_i(t)$ = Mass of injected water of H-SIT in unit time
$m_e(t)$ = Mass of evaporated water of H-SIT in unit time
C_p = Specific heat of water
T_v = Evaporating temperature
$T_{sit}(t)$ = Temperature of H-SIT during H-SIT is operated
μ_{fg} = Vaporization energy

Based on the Eqs. 1 and 2, four critical variables which are important for developing the operation strategy are identified: the amount of decay heat, temperature of H-SIT, injection mass rate from H-SIT, and evaporation mass of the coolant. As these heat removal equations are functions of time, the relation of H-SIT cooling capacity to initiation timing becomes clear.

The amount of decay heat generation is closely related with the condition of the PAFS. If both PAFSs fail from the beginning, H-SIT must be initiated in an early stage for decay heat removal. Thus the decay heat generation rate when H-SIT starts to operate is high Whereas, if PAFSs fail due to PCCT refill failure, the H-SIT initiation time is moved back because one or two PAFSs can cool down the core for a period of time. In that sense, the number of PAFSs operating before the PCCT refill failure is an important factor to develop operation strategy. Generally, it is assumed that PAFS operate for only 8 hours without PCCT refill [16].

The temperature of H-SIT coolant is also one of the critical variables; in Eq. 2, if T_{sit} increases, $T_v - T_{sit}$ decreases thus $m_i(t)$ has to increase in order to satisfy Eq. 1. T_{sit} is related with the amount of hot water flow from the pressurizer and the amount of H-SIT inventory. Hot water flow from the pressurizer is considered as a constant and the inventory of the H-SIT can be calculated based on the injection flow rate, thus in order to set the optimal H-SIT injection rate, the temperature of H-SIT should be considered.

The injection mass flow rate of each individual H-SIT cannot be controlled as they are operated by gravitational force, and is almost constant because of the fluidic device in H-SIT [17]. Thus the flow rate can be controlled by changing the number of H-SITs in operation or making an overlap between operations. The operation order can also affect to injection mass flow rate as each H-SIT is in a different location and therefore has a different length of equalizing pipe. These differences in length have an effect on the pressure balance between the RCS and the H-SITs because when the pressure is equalized through the equalizing pipe, the pressure can drop due to friction. That means, if the equalizing pipe is long, a large pressure drop occurs, leading to a decrease in H-SIT injection performance. This performance is closely related with injection flow rate.

Evaporation mass is a decay heat-related variable and is also related to the injection mass flow rate. If the injection mass rate increases, evaporation mass rate decreases because of the specific heat of cold water from the H-SIT. Concerning core safety, if the evaporation mass is higher than the injection mass, the existing coolant of the core has to be used which will eventually lead to core uncover. Therefore, the relationship between the injection mass rate and the evaporation rate should be considered carefully and systemically.

As a result, based on these critical variables, the five main factors necessary to develop the operation strategy are defined. Those are, namely, the number of PAFSs which are used simultaneously for 8 hours, the number of H-SIT operating simultaneously, the overlap percentage between operations, the initiation timing, and the operation order.

2.2 Estimation of optimal value of main factors

In the previous section, five main factors were identified. The optimum value of all factors should be analytically estimated to develop the best operation strategy. Generally, optimal values can be estimated more accurately by thermos-hydraulic code, as the computer code continually calculates the value of the variables every second, even subtle changes. An analytical approach, however, has an advantage to show the logical tendency according to amount change of variable, not focused on one specific value. Therefore, an analytical approach is preferentially performed in this section to get the basis of the global optimum point among all possible situations.

In this section, before we estimate the optimal values, the five main factors should be divided into two groups based on their dependency on the decay heat generation rate as the optimum values can vary according to any change in the initial accident condition. The decay heat generation rate at the time when the H-SITs start to operate is a representative indicator to show any change of the initial condition. Especially in SBO, the decay heat generation rate at H-SIT initiation time can be only changed through a change in the H-SIT initiation time because decay heat generation rate is a time function. This initiation time can be changed by changing the number of PAFSs in operation before the H-SITs initiate. Thus this dependency on decay heat generation shows whether the optimum value of the factors change or not, when the number of PAFS in operation changes.

Generally, initiation timing and operation order are independent factors of the number of PAFSs in simultaneous operation, so their optimal values can be estimated without any consideration of initial condition changes. These factors always have the same optimal value so are easily estimated. Whereas, the optimal value of the injection mass rate can change according to the decay heat generation rate, thus the optimal value of the number of H-SITs operating simultaneously and the overlap percentage between operations of each H-SIT can vary according to a change in the number of PAFS in operation. These factors are also correlated to each other thus are considered together to develop the operation strategy. Therefore, we need a specific estimation methodology to find the optimal value for these factors.

2.2.1 Optimal value of independent factors

2.2.1.1 Operation timing of H-SIT

Initiation timing is related with the effective use of core coolant. When PCCT refill fails, pressure and temperature of the RCS increase due to a loss of the secondary heat sink, so the POSRV should be opened to decrease RCS temperature and pressure. In this process, saturated steam is ejected through the POSRV. This is the ideal situation for decay heat removal. When, however, the POSRV opens, the pressure of the RCS dramatically decreases, leading to core and pressurizer level increase, until finally, the pressurizer becomes full and ejects hot water directly rather than saturated steam. As this hot water cannot be further used to remove decay heat by evaporation, the efficiency of the H-SITs decreases.

In that situation, if the H-SITs initiate before the pressurizer reaches full level, the inventory of the core increases when the pressurizer becomes full. That means, the pressurizer will be at full level for a relatively long time so more high-temperature water will be ejected through the POSRV. This is the important reason why H-SIT coolant cannot be used effectively when they initiate early. Therefore, the initiation timing should be delayed as long as possible. Figure 2 presents the liquid fraction of the steam which is ejected through the POSRV according to H-SIT initiation timing, calculated using MARS code. If liquid fraction is 1, only hot water is ejected through the POSRV.

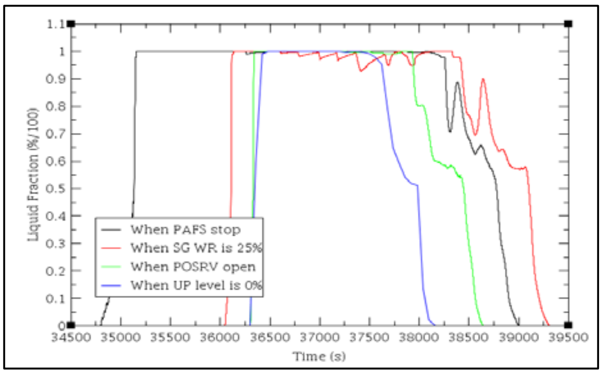

Fig. 2. Liquid fraction of ejection steam through POSRV according to operation timing of H-SIT

In this In this study, the latest timing for operation of H-SIT is considered as the time when the upper plenum level is 0%, as this means the core level is above the fuel. If the fuel is uncovered, the temperature of the core increases extremely fast and can exceed the severe accident management guideline (SAMG) entry condition without any mitigation action by the operator, it means accident situation is progressed into severe accident. Thus core uncover is not considered in this study. Therefore, theoretically, a 0% upper plenum level is the best point for H-SIT initiation timing.

2.2.1.2 Operation order of H-SIT

Differences in H-SIT efficiency according to operation order come from the differing lengths of the equalizing pipes. As previously explained, if the equalizing pipe is long, a large pressure drop occurs which decreases H-SIT injection performance. For that reason, H-SITs are distinguished according to the length of the equalizing pipes. Therefore, if H-SIT(1) has the longest equalizing pipe and H-SIT(4) has the shortest, highest-to-lowest performance of them should be H-SIT(4) - H-SIT(3) - H-SIT(2) - H-SIT(1).

When an accident occurs, the reactor trips and decay heat starts to decrease. If we consider the decrease of the decay heat generation rate, an H-SIT which has good performance should be used first. Therefore, H-SIT(4) - H-SIT(3) - H-SIT(2) - H-SIT(1) is the best order for effective use. If the H-SITs are used in reverse order, the injection rate should be increased in order to make up for the low cooling capacity of H-SIT(1).

2.2.2 Optimal value of dependent factors

The number of H-SIT operating simultaneously and overlap percentage between operations are the most difficult and complex variables to determine optimal values for because of their dependency and correlation. In order to understand the dependency of the injection mass rate (operation number and overlap percentage) on the decay heat generation rate, firstly we have to clarify the H-SIT heat removal phenomena as the injection mass rate is directly related to the amount of heat removal. The amount of heat removal by H-SIT is called H-SIT cooling capacity for convenience. The cooling capacity is calculated by using an integral calculus in Eq. 2, as shown in Eq. 3 below.

$$H_t = \int_{t_0}^{t_2} m_i(t) \times C_p \times (T_v - T_{sit}(t)) + m_e(t) \times \mu_{fg} dt \qquad (3)$$

H_t = Total cooling capacity of core
t_0 = Time when H-SIT starts to operate
t_2 = Time when core exit temperature exceed SAMG entry condition

Although Eq. 3 appears simple, the calculation of cooling capacity is not easy because from H-SIT initiation, temperature ($T_{sit}(t)$) and evaporation mass ($m_e(t)$) can change continuously and also, in an actual accident situation, the coolant injected by the H-SITs and the originally existing coolant in the core are used to cool down the core in no particular order. To solve these difficulties, we use some reasonable assumptions. In this study, H-SIT coolant is assumed to be used preferentially to make the calculation easier, so the purpose of H-SIT operation is to cool down the core without consumption of existing core coolant. Existing coolant is used after the four H-SITs are dried out. Thus Eq. 3 can be rewritten as Eqs. 4, 5, and 6 because if time exceeds t_1, $m_i(t)$ should be zero. Based on this assumption, the total amount of core inventory does not decrease until t_1. Eq. 6 is not considered in this study as it does not relate to H-SIT operation.

$$H_t = H_1 + H_2 \qquad (4)$$
$$H_1 = \int_{t_0}^{t_1} m_i(t) \times C_p \times (T_v - T_{sit}(t)) + m_e(t) \times \mu_{fg} dt \qquad (5)$$
$$H_2 = \int_{t_1}^{t_2} m_e(t) \times \mu_{fg} dt \qquad (6)$$

H_1 = Total cooling capacity of H-SIT
H_2 = Total cooling capacity of existing coolant in core
t_1 = Time when H-SIT is dried out

Another assumption is that the H-SIT injection mass all evaporates perfectly. Based on the results of section 2.2.1.1, actually, this assumption is not true. If, however, we consider that the H-SITs operate when the upper plenum level is 0%, the amount of released coolant through the POSRV without evaporation is negligible, thus, finally, maximum cooling capacity of an H-SIT is expressed as Eq. 7.

$$H_{sit} = \int_{t_0}^{t_1} m_i(t) \times C_p \times (T_v - T_{sit}(t)) + m_i(t) \times \mu_{fg} dt \qquad (7)$$

H_{sit} = Total maximum cooling capacity of H-SIT

H-SIT temperature can be calculated by considering the injection flow rate and hot steam flow from the pressurizer. This phenomenon is expressed as Eq. 8. In this study, it is assumed that the pressure of the RCS is 160bar because the POSRV operates around this pressure, maintaining RCS pressure at this value. Of course, RCS pressure has small fluctuations around 160bar because of different set points of POSRV opening and closing, but the enthalpy of the saturated steam at these different set points is not significantly different.

$$\Delta T_{sit} = \frac{m_{pzr} \times h_{pzr}}{C_p \times (m_0 - m_i(t))} \qquad (8)$$

m_{pzr} = Injection flow rate form pressurizer
h_{pzr} = Enthalpy of hot steam from pressurizer
m_0 = Initial mass of H-SIT

After arbitrary setting the injection flow rate of one H-SIT and pressurizer injection flow rate, the change in temperature is calculated and presented in Figure 3.

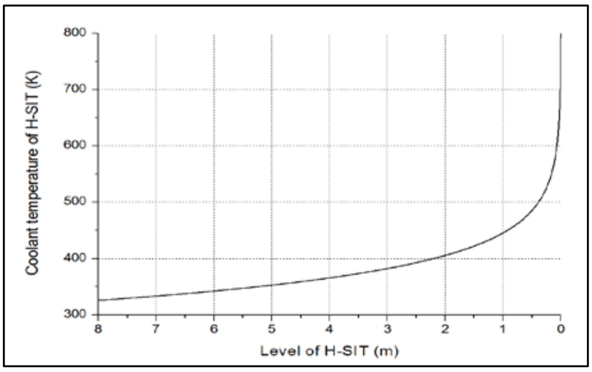

Fig. 3. Coolant temperature of H-SIT according to H-SIT level

Using Eqs. 7 and 8, maximum cooling capacity can be calculated. Cooling capacity is shown as a curve in Figure 4. Based on the equations, if the H-SIT injection flow rate increases, the capacity curve will move up, and if the flow rate decreases, the capacity curve will move down.

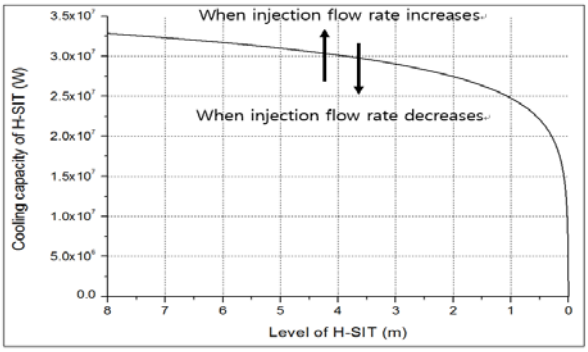

Fig. 4. Amount of cooling capacity of one H-SIT according to level of H-SIT

If mass flow is high enough, decay heat can be removed using one H-SIT only because the total cooling capacity of one H-SIT during operation is higher than the total decay heat generation. Figure 5 shows the cooling capacity under high injection mass flow. For analysis, the decay heat generation rate is calculated by using MARS code in the condition with one PAFS operating for 8 hours. If Area A ≥ Area B is satisfied, the core can be cooled down by using one H-SIT. If the injection flow rate is insufficient, the decay heat generation rate is larger than the cooling capacity, thus we have to increase the number of H-SITs which are used or overlap their operation. Figure 6 shows cooling capacity under low mass flow. In this figure, (decay heat generation rate) – (H-SIT cooling capacity) is always negative. That means the existing coolant of the core should be used, resulting in core uncover.

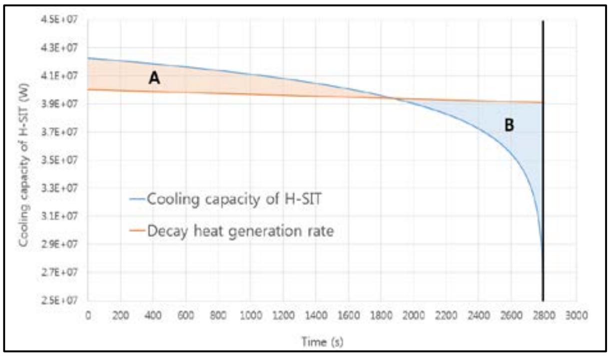

Fig. 5. Cooling capacity of one H-SIT with high flow rate under specific mass flow

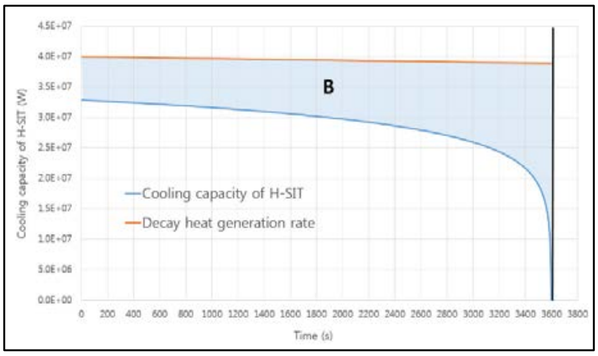

Fig. 6. Cooling capacity of one H-SIT with low flow rate under specific mass flow

To identify the optimal injection flow rate for a real accident situation, the injection flow rate of each H-SIT and injection flow from pressurizer is preferentially calculated using MARS code. Based on the results, the injection flow rate of each is 14kg/s and flow from pressurizer is 1.5kg/s. Based on the results of the analytical analysis, when one PAFS is used for 8 hours and only one H-SIT is in operation, we have to increase injection flow by more than 19kg/s. Figure 7 shows the total amount of remaining cooling capacity according to injection mass flow. If two PAFSs are used for 8 hours, injection mass flow over 18.4kg/s is enough to mitigate an accident. Figure 8 shows the amount of total remaining cooling capacity according to mass flow when two PAFSs are used for 8 hours. Based on these results, even if two PAFSs are used before H-SIT initiation, injection mass flows sufficient for cooling from a single H-SIT in both cases are not much different as the decay heat generation rate in both cases are not much different.

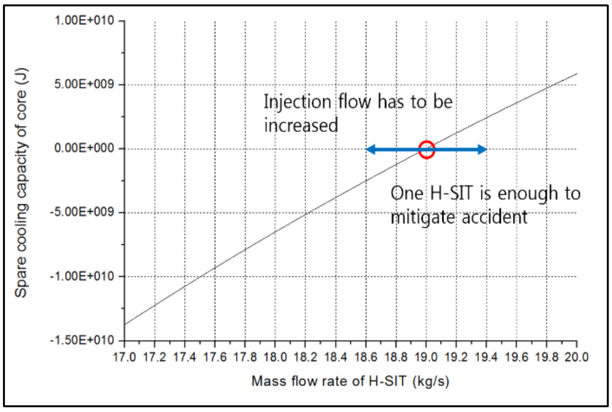

Fig. 7. Total amount of spare cooling capacity of H-SIT according to injection mass flow

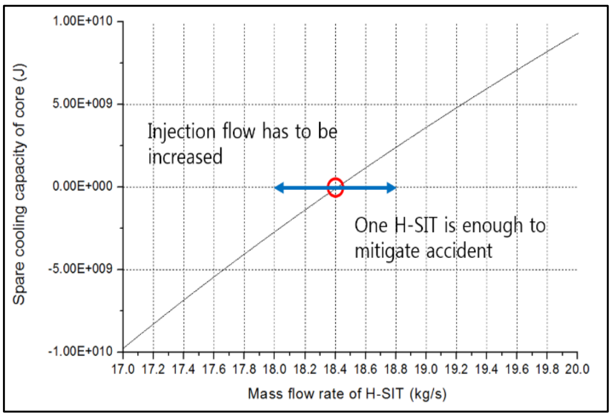

Fig. 8. Total amount of spare cooling capacity of H-SIT according to injection mass flow

If the remaining capacity (total H-SIT capacity – total decay heat generation) is at or above zero, the core is safe in both cases because the injection mass is sufficient to remove decay heat. However, in view of efficiency, any remaining capacity larger than zero is not ideal, as this implies that H-SIT coolant is injected excessively in comparison with the minimum necessary amount to cool down the core.

If excessive coolant is injected (m_i-m_e is very high), hot water may be ejected in liquid state rather than hot steam when the POSRV opens. Further, the coolant can get stuck in other places such as a hot leg due to water slug formation [18]. Therefore, the ideal flow rate results in zero remaining cooling capacity.

If the remaining capacity is negative, injection mass is insufficient to remove the decay heat and must be increased. As explained previously, there are two ways to increase injection mass: increase the number of H-SITs operating from the beginning, or overlap H-SIT operation. If injection flow rate must be significantly increased, it is preferable to increase the number of H-SITs in operation. If only a slight increase is necessary, overlapping the H-SITs operation is sufficient.

When H-SIT start times are staggered, the overlap between two H-SITs results in similar cooling capacity as when they initiate simultaneously. As shown in Figure 8, two H-SITs overlap during A1, A2, and A3. In these areas, there is positive remaining capacity. Whereas, there is a negative remaining capacity in B1, B2, B3, and B4. Thus, if the sum of A1, A2, A3 ≥ the sum of B1, B2, B3, B4, the core is safe until the H-SITs are dried out. Considering the maximum efficiency as explained previously, the sum of A1, A2, A3 = the sum of B1, B2, B3, B4 is used to calculate the optimal overlap percentage.

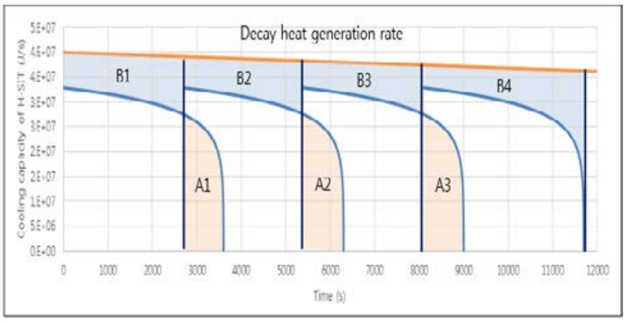

Fig. 9. Cooling capacity of all H-SITs under specific mass flow

Overlapping operation is used to increase the injection flow rate slightly. If, however, the overlap percentage reaches 66%, the injection flow rate is similar to when two H-SITs operate from the beginning without overlap. Thus if an overlap percentage of greater than 66% is required, increasing the number of H-SITs is recommended. This case can be called a dual overlap, with two H-SITs initiating simultaneously and overlapping with the remaining two H-SITs. 66% is obtained through the average flow rate calculation. If the injection flow rate of one H-SIT is m_α, then the rate of two H-SITs is $2m_\alpha$. Figure 9 demonstrates these injection flow rates with an operation overlap of 50%.

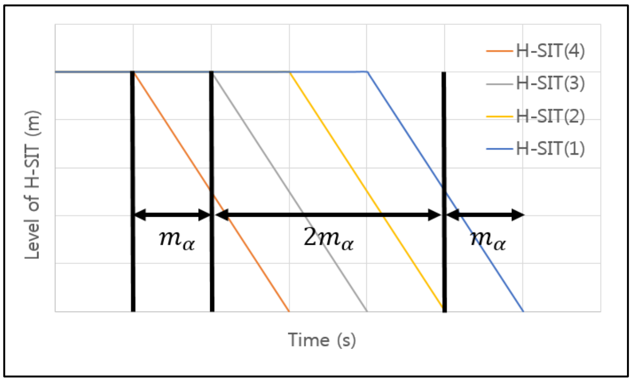

Fig. 10. Averaged mass injection rate of H-SIT according to level of H-SIT

In Figure 10, the average mass flow rate is $1.6m_\alpha$, from dividing total injection mass by total injection time (Eq. 9). If the average injection flow rate is over $2m_\alpha$, the overlap percent k has to be larger than 66%.

$$\left(\frac{4}{4-0.03k}\right) \times m_\alpha \qquad (9)$$

k = Overlap percentage of H-SIT

In this study each H-SIT injection flow rate is assumed to be the same because of their same design characteristic. Based on Figures 7 and 8, the H-SITs should be overlapped even when the PAFSs have operated for 8 hours. To calculate the optimal overlap percentage, an analytical study is carried out with novel methodology explained in figure 8 using the matlab program. Figure 10 shows the total amount of remaining cooling capacity of the H-SITs according to the overlap percentage.

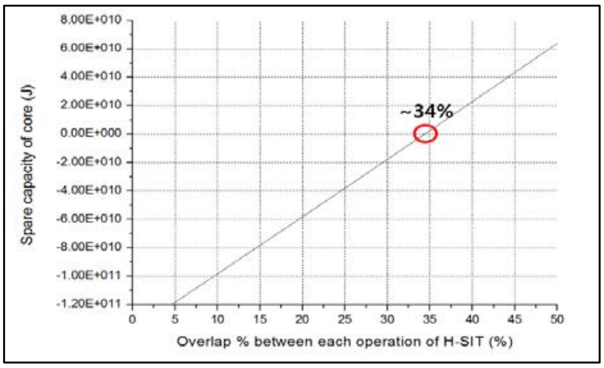

Fig. 10. Total amount of spare cooling capacity of H-SIT according to overlap percent when one or two PAFSs are available.

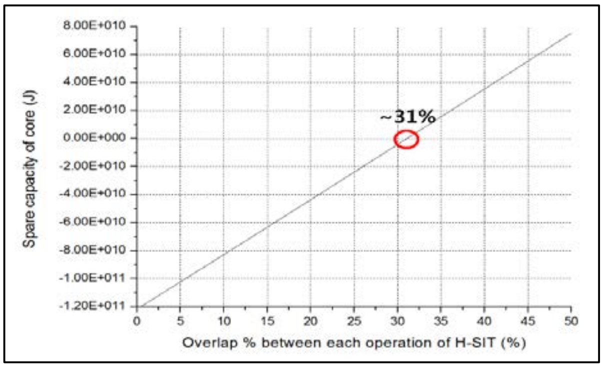

Fig. 11. Total amount of spare cooling capacity of H-SIT according to overlap percent when one or two PAFSs are available.

Based on the results of the analytical study, at least a 34% overlap percentage is needed to prevent core uncover when one PAFS is used for 8 hours. Thus, the H-SITs should be used by overlapping two by at least 34%. If two PAFSs are used for 8 hours, the minimum overlap percentage is 31%. This is similar to the case with one PAFS in operation, as the decay heat generation rate of these two cases is not much different.

When both PAFSs fail, if one H-SIT is used from the beginning, the H-SITs should be overlapped by more than 74%; thus we have to consider two H-SITs used from the beginning. In this case, the H-SITs should overlap by 4.6% to maintain core safety. Figures 11 show the total amount of remaining cooling capacity of the H-SITs when two PAFSs both fail.

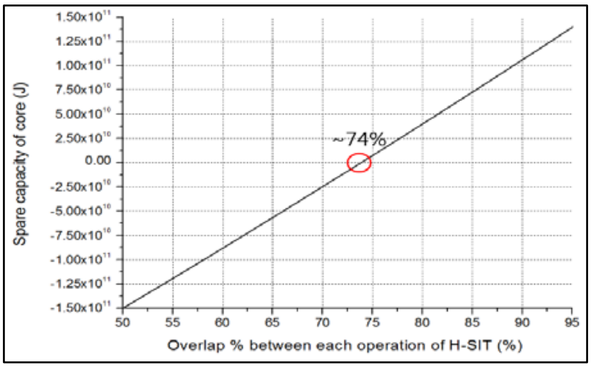

Fig. 12. Total amount of spare cooling capacity of H-SIT according to overlap percent when two PAFSs are all failed

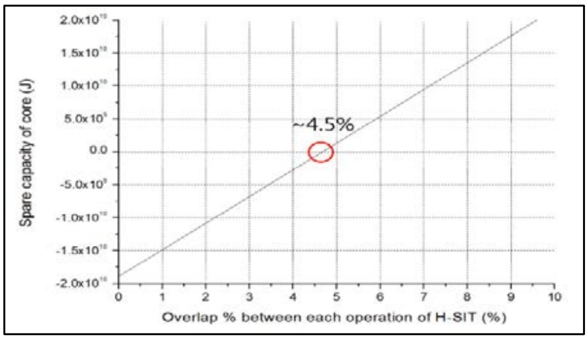

Fig. 13. Total amount of spare cooling capacity of H-SIT according to overlap percent when two PAFSs are all failed.

3. Conclusions

An optimum operation strategy for an H-SIT system in SBO was developed in this paper. In order to develop this operation strategy, five main factors were identified: the number of PAFSs in simultaneous operation before PCCT refill failure, the number of H-SITs in simultaneous operation, and the overlap percentage, initiation timing, and operation order of the H-SITs. Based on these main factors, the optimum values were identified by analytical and theoretical studies. Results demonstrated that the H-SITs should initiate when the upper plenum level is 0%, and should operate in a 4-3-2-1 order. In case of overlap percentage, it varies according to the number of PAFSs in operation for 8 hours. With both PAFSs in operation before H-SIT initiation, the optimum overlap percent was found to be 31%, with a value of 34% for one PAFS in operation before H-SIT initiation. The results of these two cases are not much different as the decay heat generation rate in both cases is similar. When both PAFSs fail to operate, the result of analytical study demonstrated the H-SITs should overlap by 74%, as the decay heat generation rate during H-SIT operation was very high compared to the other cases. In this case, with dual overlap of the H-SITs in simultaneous operation, a 4.6% overlap is sufficient to mitigate the accident. . The results of the analytical study have an important role in respect to giving a logical background to find the global optimum values of all possibilities of overlap percentage thus this approach can help to solve the imitation of code simulation. General tendency of phenomena is hard to see using code simulation as it simulate only one case by one time Therefore, if code simulation can be performed with basis of global optimum value, it can be more accurate and realistic study.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Power Core Technology Development program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and was granted financial resources from the Ministry of Trade, Industry & Energy, and Republic of Korea (No. 20131510101670).

REFERENCES

[1] Yang, J. E. (2014). Fukushima Dai-Ichi accident: lessons learned and future actions from the risk perspectives. Nucl. Eng. Technol. 46(1), 27-38.

[2] Song, J. H., & Kim, T. W. (2014). Severe accident issues raised by the Fukushima accident and improvements suggested. Nucl. Eng. Technol. 46(2), 207-216.

[3] Chang, S. H., Kim, S. H., & Choi, J. Y. (2013). Design of integrated passive safety system (IPSS) for ultimate passive safety of nuclear power plants. Nucl. Eng. Des. 260, 104-120.

[4] Cherubini, M., Muellner, N., D'auria, F., & Petrangeli, G. (2008). Application of an optimized

AM procedure following a SBO in a VVER-1000. Nucl. Eng. Des. 238(1), 74-80.

[5] Chang, C. J., Lee, C. H., Hong, W. T., & Wang, L. L. (2006). IIST small break LOCA experiments with passive core cooling injection. Nucl. Eng. Des. 236(1), 19-34.

[6] Buchner, H., & Fabian, H. (1994). Comparative evaluation of active vs passive system designs. Rel. Eng. Sys. Safety 45(1), 195-200.

[7] Kim, M. S., Cheon, J., & Kang, S. H. (2010). The development of a passive auxiliary feedwater system in APR+. In Proceedings of the 2010 International Congress on Advances in Nuclear Power Plants-ICAPP'10.

[8] Liu, M., Erkan, N., Ishiwatari, Y., & Okamoto, K. (2015). Passive depressurization accident management strategy for boiling water reactors. Nucl. Eng. Des. 284, 176-184.

[9] Kwon, T., & Park, C. (2013). Hybrid SIT for Passive Safety System. Transactions of the Korean Society Spring Meeting. 549 page, May 30-31.

[10] Kim, B. G., Yoon, H. J., Kim, S. H., & Kang, H. G. (2014). Dynamic sequence analysis for feed-and-bleed operation in an OPR1000. Ann. Nucl. Energy, 71, 361-375.

[11] Volkanovski, A., & Prošek, A. (2013). Extension of station blackout coping capability and implications on nuclear safety. Nucl. Eng. Des. 255, 16-27.

[12] Jeon, I. S., & Kang, H. G. (2015). Development of an operation strategy for a hybrid safety injection tank with an active system. Nucl. Eng. Technol 47(4), 443-453.

[13] Jeong, J. J., Ha, K. S., Chung, B. D., & Lee, W. J. (1999). Development of a multi-dimensional thermal-hydraulic system code, MARS 1.3. 1. Ann. Nucl. Energy 26(18), 1611-1642.

[14] Darnowski, P., Skrzypek, E., Mazgaj, P., Świrski, K., & Gandrille, P. (2015). Total loss of AC power analysis for EPR reactor. Nucl. Eng. Des. 289, 8-18.

[15] Lamarsh, J. R., Baratta, A.J (2001). Introduction to nuclear engineering. Prentice Hall Upper Saddle River, third ed. New Jersey.

[16] Cheon, J., & Kim, H. G. (2010). Design Characteristics of the Passive Auxiliary Feedwater System in APR+. Transactions of the Korean Society Autumn Meeting. October 21-22

[17] Chu, I. C., Song, C. H., Cho, B. H., & Park, J. K. (2008). Development of passive flow controlling safety injection tank for APR1400. Nucl. Eng. Des. 238(1), 200-206.

[18] Kordyban, E. S., & Ranov, T. (1970). Mechanism of slug formation in horizontal two-phase flow. Journal of Fluids Engineering, 92(4), 857-864.