IMPROVEMENT OF LOCA CORE DAMAGE FREQUENCY BASED ON BEST-ESTIMATED THERMAL-HYDRAULICS ANALYSIS

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The object of this research is to obtain the realistic results of Loss Of Coolant Accident (LOCA) core damage frequency reflecting a success criteria analysis using best-estimated thermal-hydraulics code. To do this, firstly, identification of the characteristics of Nuclear Power Plant (NPP) response for the all break size of cold-leg LOCA was conducted. After that, quantification of LOCA core damage frequency was obtained by restructuring the all event trees based on thermal-hydraulics results. The several results were obtained as followings. In the small break size below the 1.4 inch, decay power is well removed by only normal secondary cooling. Using the only one High Pressure Safety Injection (HPSI) pump, reactor core is properly cooled from 0.8 inch to 9.4 inch break size. Thermal hydraulics results showed that just below the 0.8 inch needs feed and bleed operation. Based on thermal hydraulic results, five new event trees were developed: very small, small, medium, large, and very large LOCA. Core damage frequency of new LOCA Event Trees (ETs) is 5.80E-07 and it is 12% less than conventional one. From this research, we obtained not only thermal-hydraulics characteristics for entire break size of LOCA in view of deterministic safety assessment, but also more realistic core damage frequency of the LOCA using updated information. The difference between the results in this research and conventional knowledge could be used to modify the current Emergency Operation Plan (EOP) and to design another NPP type.

I. Introduction

In probabilistic safety assessment (PSA), the LOCA is considered as the one of the most important initiating events. Since the publication of WASH-1400 in 1975 and the division of the LOCAs into three groups in the report[1], almost the PSA model, up to now, has undoubtedly adopted the three groups of LOCA and even an exact break size boundary that they used. Against this background, for the pressurized water reactor (PWR), the conventional PSA model divides the LOCAs into three groups along the break sizes: the small break size (below 2.0 inches), medium break size (from 2.0 to 6.0 inches), and large break size (above 6.0 inches).

With the awareness of the importance for a realistic PSA for a risk-informed application, several studies related to the LOCA have been conducted. Han and co-authors (2007) assessed the feasibility of a method to estimate an operator's action for a small break LOCA without a high pressure safety injection (HPSI) for the Korea Standard Nuclear Power Plant (KSNP). This showed that normal secondary cooling could be a success criterion in the small LOCA without safety injection, although it is contrast with the conventional PSA. Furthermore, another study performed thermal-hydraulics calculations for the LOCA in order to improve the accident sequences and success criteria of the event tree.[2] However, in this study, the number of groups and break size boundary in the conventional PSA were used and the core damage frequency was not quantified. In addition, Technical University of Madrid suggested the integrated safety assessment for the LOCA; the group of authors concluded that the present emergency operating procedures (EOPs) are adequate for managing accidents.[3] However, this study did not focus on the PSA model and quantification of the core damage frequency.

The purpose of the present research is to obtain realistic results of the LOCA core damage frequency based on the success criteria analysis using the best-estimated thermal-hydraulics code. For this purpose, we first identify the characteristics of NPP response for the all break size of cold-leg LOCA. Next, the quantification of the LOCA core damage frequency is obtained by restructuring all event trees based on the thermal-hydraulics results.

II. Materials and Method

II.A. MARS KS model for KSNP

In order to obtain the general characteristics of the thermal-hydraulics behavior in the LOCA, Korea Standard Nuclear Power Plant (KSNP), whose name originates from Optimized Power Reactor 1000 (OPR 1000), was selected. The KSNP is one of the NPPs types developed in South Korea. Among 32 units of NPPs (including constructing) in South Korea, 10 units are KSNP. This is the pressurized water reactor with 1,000MWe of electricity generation. There are two coolant loops, one steam generator (SG), and two reactor coolant pumps (RCPs) for each loop.

The MARS code has been developed by KAERI based on the RELAP5/MOD3 and COBRA-TF codes.[4,5] KAERI has developed the MARS input model of KSNP for a realistic analysis of small- and large-break LOCAs.[6] Fig.1 shows the nodalization scheme of the MARS input model for the LOCA calculation for KNSP. Pipe rupture occurs in the middle of one cold-leg line among the four lines. The break point is located in the after the RCP.

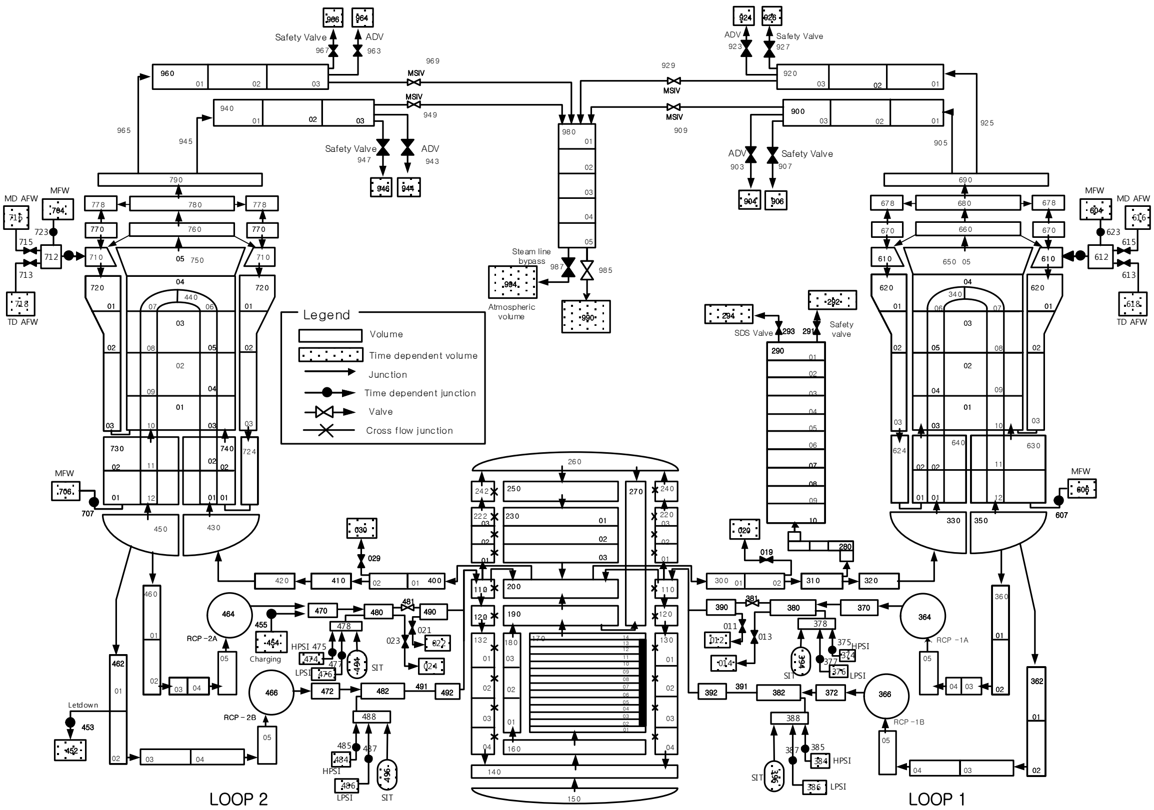

Fig. 1. Nodalization scheme of the MARS input model for the LOCA calculations of the KSNP

II.B. Calculation Matrix

The ASME/ANS PSA standard defines core damage as “uncover and heat-up of the reactor core to the point at which prolonged oxidation and severe fuel damage are anticipated and involving enough of the core”.[7] In the study regarding to the success criteria[8], NRC used a PCT of 1,204^{o}C (2,200^{o}F) as the core damage condition, because the timing between 1,204oC and oxidation transition is relatively similar among the different sequences analyzed.

In order to identify the thermal-hydraulics behaviors with several combinations of available safety functions/features when the cold-leg LOCA occurs the three categories outlined below were considered.

II.B.1. Safety Injection Only

In the conventional PSA work regarding with medium and large break size LOCAs, safety injections are the main safety function to prevent core damage. KSNP adopted the HPSI, LPSI, and SIT as the safety injection features. In a small break size LOCA, the RCS pressure does not decrease, as pressurization due to the decay power is larger than depressurization due to a leakage. In that case, HPSI is not available. If we assume that secondary cooling is also not available, the EOP of KSNP leads an operator to open the SDS valve in order to decrease the RCS pressure. The analysis cases considered in the present study are outlined below.

- HPSI only available for the LOCAs of all break sizes
- HPSI + SIT available for the LOCAs of all break sizes
- HPSI + SIT + LPSI available for the LOCAs of all break sizes
- The SDS valve + HPSI available for the LOCAs of all break sizes

II.B.2. RCS Cooling by SG Only

In both deterministic and probabilistic safety assessments of the cold-leg LOCA, safety injection is defined as an essential function to prevent core damage by supplementing the RCS coolant. The small break size LOCA in the conventional PSA does not accept the case of RCS cooling by SG without safety injection as a success branch. However, evidence is available of success possibility for RCS cooling by SG without HPSI.[9] As a small amount of leakage may be not severe for the reactor core cooling, the SG cooling without HPSI can sufficiently remove the entire decay power. Based on the EOP of KSNP, an operator should open ADV in order to cool-down the RCS. By flowing auxiliary feed water from the inlet to the main steam line, SG removes the decay power. For this purpose, the coolant inventory of the primary side in SG should be sufficient. That is the reason why the RCS cooling by SG only is available for a small break size LOCA.

In this case, the RCS cooling rate and the operator action time can be movable variables. In the present study, we assumed that ADV is opened by an operator after 25 minutes from the reactor scram and that the RCS cooling rate is consistently maintained with 45K/hr due to the perfect performance of the operator. The RCS cooling by SG without HPSI for a small break size LOCA was considered in this study. The RCS cooling by SG is called normal secondary cooling.

II.B.3. Combination of Safety Injection and RCS Cooling by SG

NPP's using both safety injection and RCS cooling by SG maximizes the probability of success. In a small break size LOCA, normal secondary cooling leads to the RCS to depressurize and makes HPSI available. In this case, normal secondary cooling performs a similar function to that of the SDS valve. In medium or large break size LOCAs, more HPSI coolants are injected to the reactor core as compared with the HPSI only case. It is because the RCS cooling by SG lowers the RCS pressure, then the injected flow rate by HPSI increases due to the low resistance head. Thus, the combination of safety injection normal secondary cooling makes the core safe up to the break size which is larger than that in the HPSIP only case.

III. Results

II.A. Thermal Hydraulics Analysis

II.A.1. Base Case

To obtain the general characteristics of the RCS temperature and coolants of NPP when a LOCA occurs, the base case simulations were conducted. All safety functions, including safety injection and normal secondary cooling, were not available in the base case simulations. All break sizes of the LOCA from 0.5 to 60.0 inches (guillotine break) were considered. Fig.2 shows the simulation results of the timing of the reactor trip and the PCT limit for the base case simulations. The reactor trip was generated by the pressurizer low pressure trip for all break sizes. The reactor trip of a 0.5-inch break size LOCA occurs at 1,400 seconds. The time to the PCT limit (PCT=1,477K) in the case of a 0.5-inch break size LOCA is 8,500 seconds. These two variables decrease with the increase of the as break size, as a larger break size makes a larger coolant leakage and causes a rapid pressure drop and a rapid exhausting of the RCS coolant. At a 0.5-inch break size LOCA, from the time when an operator recognizes the accident from the reactor trip, the reactor core has 117 minutes until the core damage. However, this time margin decreases with the increase of the break size. At a 2.5-inch break size, the time margin is 30 minutes. This means that, since the break size is larger, NPPs cannot expect the operator's action for the safety of NPPs. Thus, when a large break LOCA occurs, the safety of the reactor core is expected to be ensured by the automatically operated safety function, rather than by an operator's manual action.

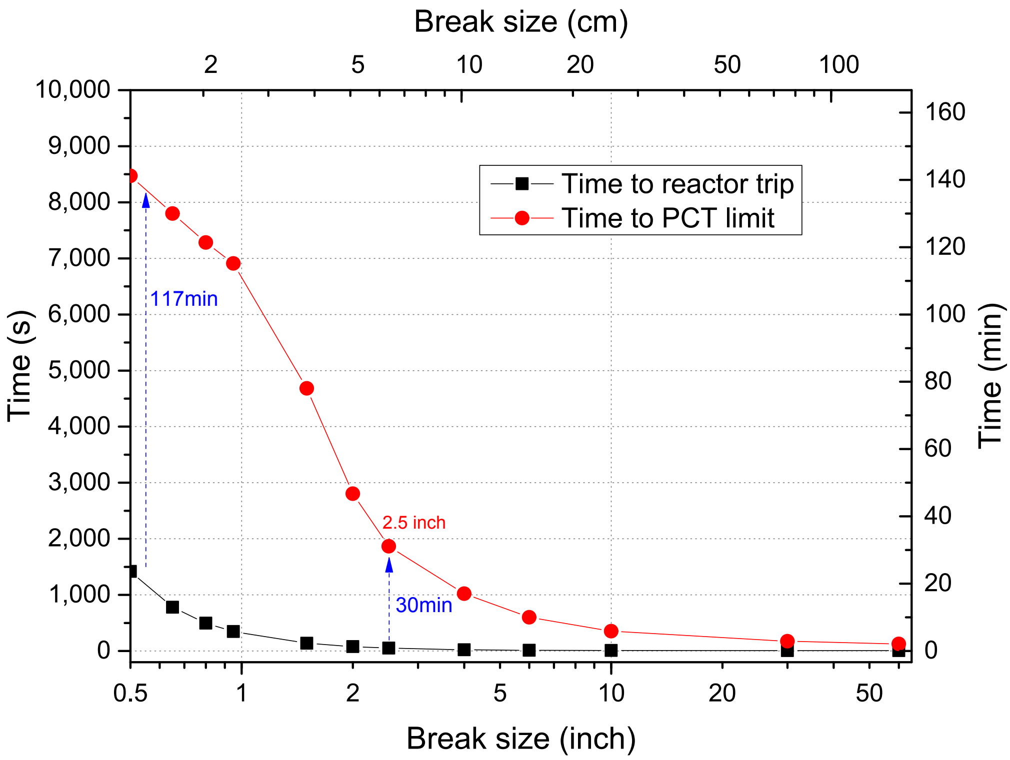

Fig. 2. Simulation results of the timing of the reactor trip and the PCT limit for the LOCAs of all break sizes (base case: no safety function)

II.A.2. Safety Injection Only

Fig.3 shows the simulation results of the timing of the PCT limit for LOCAs of all break sizes when only one HPSI pump was available. For the break size of the range between 0.5 and 0.7 inches, the PCT reaches the limit (1,477K) from 180 to 270 minutes after the LOCA occurrence. It is because the RCS pressure is not sufficiently depressurized to inject the HPSI. For LOCAs of the break size from 9.5 inches to the guillotine size, PCT also reaches the limit. The time to the PCT limit with HPSI available is very similar to the time to the PCT limit with no safety function. The released RCS coolant is considerably larger than the supplemented coolant by HPSI. The core is unrecovered due to mass unbalancing between the in-flow and the out-flow coolant within the RCS boundary, then is damaged within 10 minutes after a LOCA occurs. There was no core damage within 24 hours for LOCAs of the break size between 0.8 and 9.4 inches. It means that the amount of leakage for the LOCAs of this break size can be properly handled by one HPSI pump for the RCS safety.

For the LOCAs of small break size, such as from 0.5 to 0.7 inches, safety injection is not activated, because the low leakage rate increases the RCS pressure. In this small break LOCA, injection by the HPSI pump is sufficient to cover the small leakage rate. Thus, considering the acting pressure of HPSI, an additional operator action is needed to decrease the RCS pressure and inject the coolant to RCS. KSNP suggests the SDS valve to do that. This plays the same role as a pilot-operated safety relief valve (POSRV) of APR 1400. According to the EOP of KSNP, the SDS valve should be used when the RCS pressure remains high. If the RCS pressure increases to the PSV open pressure, then operators should open the SDS valve in order to decrease the RCS pressure. We term this the feed and bleed operation.

In the case of one HPSI pump and two SITs are available for safety injection. The volume is about 68 m^3 for each SIT. Coolant in SIT is passively injected at below 4.2e6 pa (609 psi). Due to the SIT injection, no core damage region is extended to 17.8 inches, as compared to the HPSI only case.

In the design of KSNP, the LPSI pump has an essential safety function for the LOCAs of a large break size, including the guillotine size break. In other words, for a large break size LOCA, there is no way to prevent the core damage, if LPSI is not available. The most severe case is that of a 60-inch break size, i.e., the guillotine double ended break. Since the KSNP was designed such that LPSI is not available after the exhaustion of RWST, HPSI is requisitely needed for a long-time core cooling. For this reason, we do not need to consider the LPSI only available case.

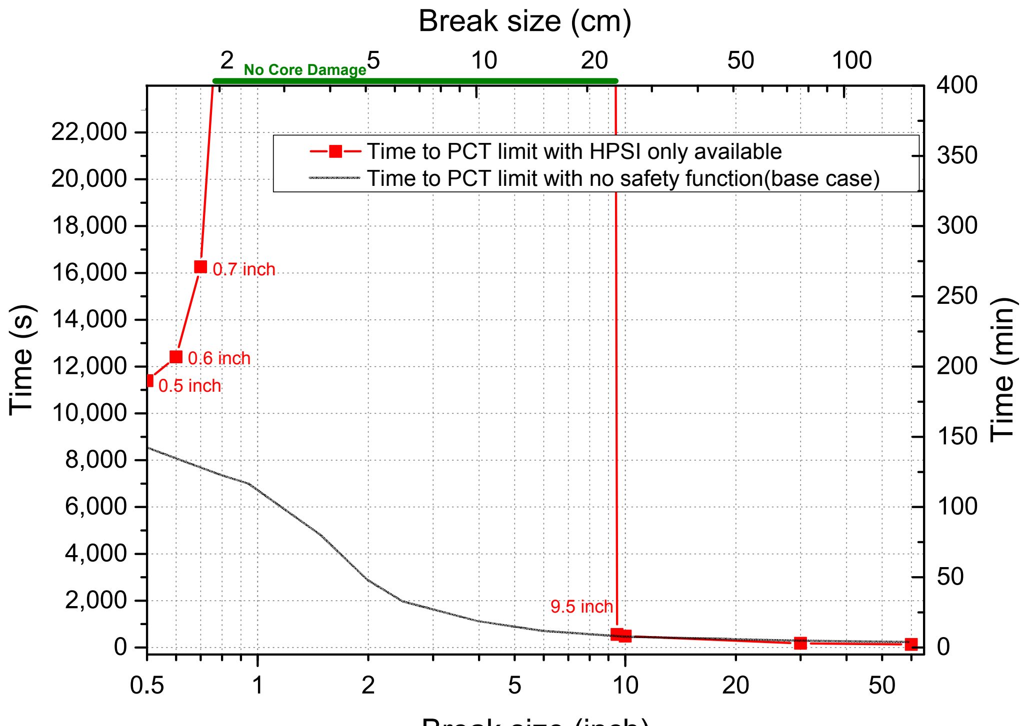

Fig. 3. Simulation results of the timing of the PCT limit for LOCAs of all break sizes (HPSI only available)

II.A.3. Normal Secondary Cooling

Fig.4 shows the simulation results of the timing of the PCT limit for the LOCAs of all break sizes when normal secondary cooling available. Normal secondary cooling was simulated by modeling the ADV opening with the RCS cooling rate of 45K. The flow rate of the AFW pump was controlled by the SG water level. For the LOCAs of below than 1.4-inch break size, the reactor core was cooled by only normal secondary cooling without HPSI. The accumulated leakage coolant masses at the 24 hour for 1.1-, 1.2-, and 1.3-inch break sizes were about 141, 149, and 161 ton, respectively. Also, at that time, the leakage rates were about 0.165, 0.166, and 0.176 kg/s, respectively. Compared to the initial leakage rate (58, 69, and 81 kg/s), these are almost zero. It means that at the time above 24 hours, the accumulated leakage coolant mass is not different from that of 24 hours and reactor core will be also safe after 24 hours. For above ca. 170 ton of the accumulated leakage mass, the reactor core was damaged. For above a 2.0-inch break size LOCA, the timing of the PCT limit is identical to the results for the no safety function case. In those regions, a large release of leakage coolant makes the primary side of SG empty in the beginning. Thus, normal secondary cooling cannot remove the decay power.

II.A.4. Combination of Safety Injection and Normal Secondary Cooling

When normal secondary cooling is also available with HPSI, we can expect that the range of the no core damage condition is not different from the HPSI only case for the upper limit of break size. It is so because the large release of leakage coolant makes the primary side of SG empty in the beginning. In this kind of a situation, normal secondary cooling is useless for cooling; then, only HPSI is available to remove the decay power. For the low break size, normal secondary cooling could be well operated for the RCS depressurization. It plays the same role as the SDS valve opening. Thus, it is expected that the combination of HPSI and normal secondary cooling makes no core damage region extend to below than 0.8-inch break size. As shown in Fig.5, break sizes from 0.5 to 10.2 inches are the region of no core damage when the HPSI and normal secondary cooling are available.

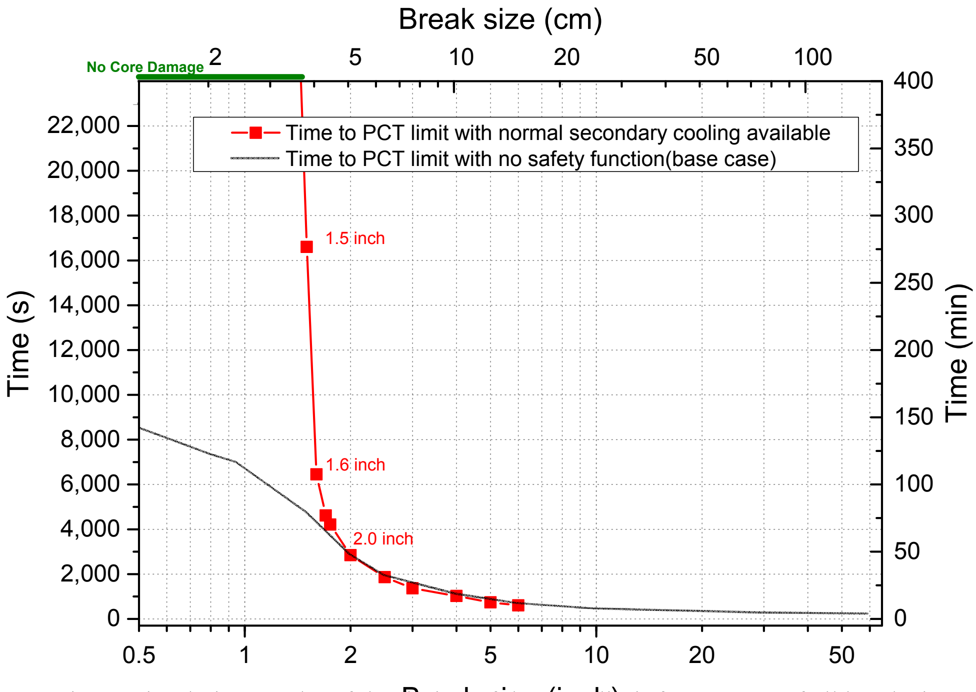

Fig. 4. Simulation results of the timing of the PCT limit for LOCAs of all break sizes (normal secondary cooling available)

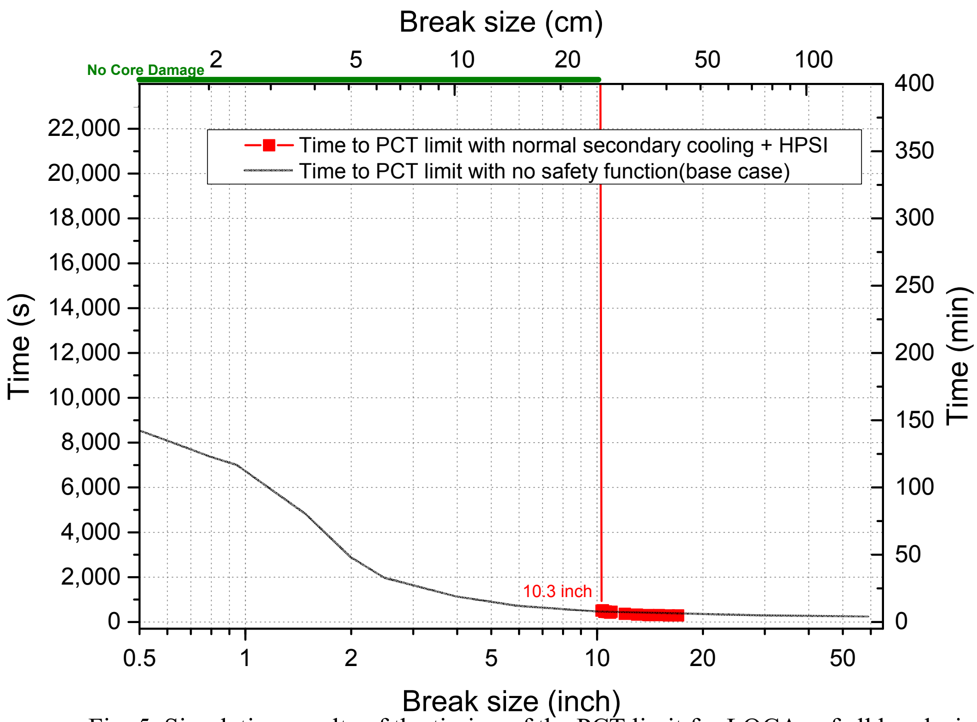

Fig. 5. Simulation results of the timing of the PCT limit for LOCAs of all break sizes (normal secondary cooling + HPSI available)

II.A.5. Discussion

In general, the RCS coolant inventory and the RCS pressure are mutually proportional. When the RCS coolant inventory is low, then the RCS pressure is also low. We divided the RCS pressure into three parts. When the RCS pressure remains high, then safety injection is unavailable as the first part. When the RCS pressure decreased only enough for HPSI, then only HPSI is available. When the RCS pressure decreased even enough for LPSI, then LPSI is also available as well HPSI. For the RCS coolant inventory, there was a critical point of the accumulated leakage mass that made the core damage. Above this critical point, there was no need for safety injection. On the other hand, below the critical point, safety injections were needed. Since the release mass in some regions of break size has a significantly insufficient RCS inventory, LPSI should be needed. There are nine sections which have their own characteristics (see Fig.6). Using this domain, five groups of the LOCAs of all break sizes can be derived.

For the very small break size region (Group I), from 0.5 to 0.8 inches, the RCS inventory remains above the critical point and the RCS pressure is not depressurized by a leakage. Since HPSI is not available if there is no RCS depressurization, the SDS valve opening or normal secondary cooling are needed in order to decrease the RCS pressure. The leakage mass is small enough to be below the critical point; thus, only normal secondary cooling makes no core damage. Therefore, success criteria of Group I are the feed and bleed operation, normal secondary cooling, and HPSI with normal secondary cooling.

For the small break size region (Group II), from 0.8 to 1.4 inches, the RCS inventory remains also above the critical point and the RCS pressure is depressurized to the HPSI pump available pressure level. Since the leakage mass is above the critical point, normal secondary cooling is also possible to remove the decay power well. Without any additional depressurization, HPSI is available. Thus, all safety injections, including HPSI, also make no core damage. Therefore, success criteria of Group II are the HPSI only case and normal secondary cooling.

For the medium break size region (Group III), from 1.4 to 9.4 inches, the RCS inventory decreases below the critical point and the RCS pressure is depressurized to the HPSI available pressure level. Due to the sufficient RCS inventory, HPSI should be injected to RCS. The difference between Group II and III is normal secondary cooling. Normal secondary cooling is a success criterion in the small break size region, whereas it is not a success criterion in the medium break size region. All safety injections, including HPSI, make no core damage. Thus, the success criterion of Group III is the HPSI only case.

For the large and very large break size regions (Group IV, from 9.4 to 17.8 inches; Group V, from 17.8 to 60.0 inches), the RCS inventory is released below the critical point and the RCS pressure is depressurized to the LPSI available pressure level. Since the RCS coolant inventory is significantly insufficient, an additional safety injection is needed in these groups. The success criterion of Group IV is the HPSI with SIT case. The success criterion of Group V is the LPSI with HPSI case.

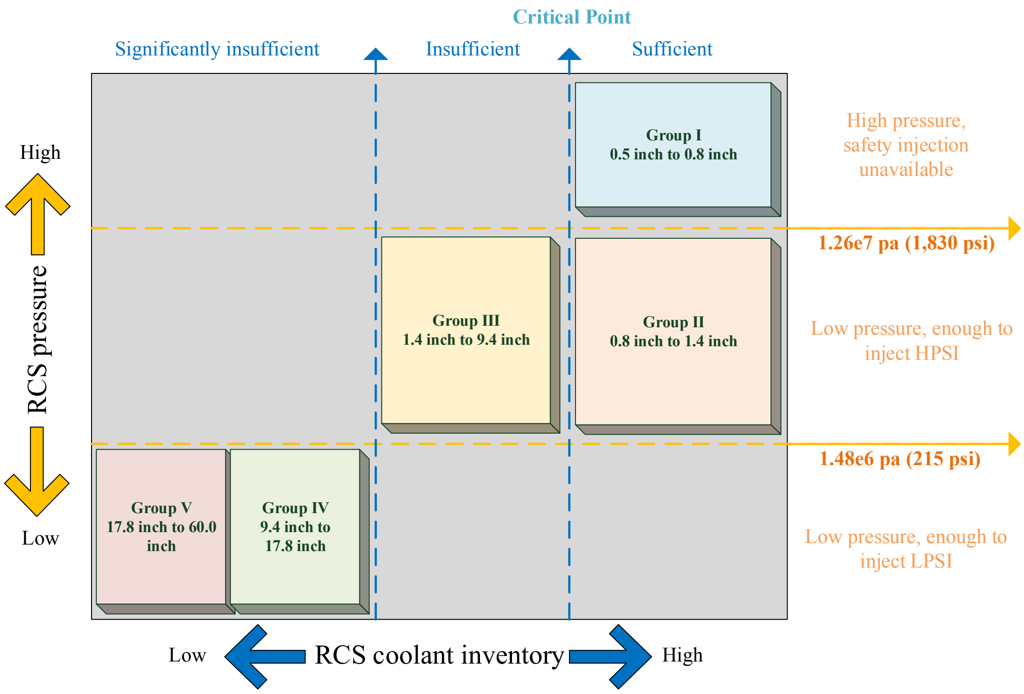

Fig. 6. Characteristics of thermal-hydraulic transients for each break size group

II.B. PSA Model

Based on new insights obtained from the thermal-hydraulics results for the LOCAs of all break sizes, we found that the conventional PSA model is not well reflected in the real estimation. There are three groups (small, medium, large) in the conventional PSA LOCA model and each group's success criteria do not explain the real situation. Furthermore, the break size boundaries between the groups do not match the new results well.

The success criteria of each group are as follows:
Bleed RCS is a bleed operation by opening the SDS valve, CSR is the containment spray recirculation, H/C Recirculation is the hot-leg and cold-leg recirculation.

- VSLOCA:
  1) Reactor Trip * HPI * Bleed RCS * HPI Recirculation * CSR
  2) Reactor Trip * HPI * Normal Secondary Cooling * CSR
  3) Reactor Trip * Normal Secondary Cooling * CSR
- SLOCA:
  1) Reactor Trip * HPI * HPI Recirculation * CSR
  2) Reactor Trip * Normal Secondary Cooling * CSR
- MLOCA: HPI * HPI Recirculation * H/C Recirculation * CSR
- LLOCA: SIT * HPI * HPI Recirculation * H/C Recirculation * CSR
- VLLOCA: LPI * HPI * HPI Recirculation * H/C Recirculation * CSR

Table 1 shows the core damage frequency results. In the results of the conventional LOCA classification, the LOCA core damage frequency is 6.61E-07 (/y) and it is 24.9% of the total core damage frequency, 2.65E-6 (/y). Among the three groups of the LOCAs, the core damage frequency of small and medium LOCAs was about 99%, and remainder amounted to 1% for large LOCAs. This large difference originates from the difference of their initial frequency, because the initial frequency of small LOCAs is 120 times larger than that of large LOCAs.

In the results of the updated LOCA classification which consists of five break size groups, the LOCA core damage frequency is 5.80E-7 (/y) and it amounts to 22.6% of the total core damage frequency, 2.57E-6 (/y). The LOCA core damage frequency is about 88% (5.80E-07/6.61E-07) of that in the original model.

TABLE I. Core damage frequency results using the conventional PSA ET and the updated PSA ET

	Conventional LOCA classification					Updated LOCA classification				
	Break size (inches)	Initial Frequency (/y)	CDF (/y)	Internal Ratio (%)	Ratio to total CDF (%)	Break size (inch)	Initial Frequency (/y)	CDF (/y)	Internal Ratio (%)	Ratio to total CDF (%)
Very small LOCA						0.5-0.8	1.90E-04	1.22E-07	21.0	4.7
Small LOCA	0.5-2.0	3.49E-04	3.02E-07	45.7	11.4	0.8-1.4	1.18E-04	7.51E-08	12.9	2.9
Medium LOCA	2.0-6.0	1.62E-04	3.52E-07	53.2	13.3	1.4-9.4	2.03E-04	3.78E-07	65.1	14.7
Large LOCA	6.0-60.0	2.89E-06	7.00E-09	1.1	0.3	9.4-17.8	4.50E-07	8.27E-10	0.1	0.0
Very large LOCA						17.8-60.0	2.26E-06	4.71E-09	0.8	0.2
Total		5.14E-04	6.61E-07	100.0	24.9 (Total CDF: 2.65E-6)		5.14E-04	5.80E-07	100.0	22.6 (Total CDF: 2.57E-6)

IV. Summary and Conclusion

The main results of the present paper can be divided into two parts. The first part is the thermal-hydraulics analysis cold-leg LOCAs of all break sizes. This is for identifying the characteristics of NPP transients at LOCA and for defining the safety functions for each break size spectrum as the success criteria. For this purpose, we used the MARS code. The second part is the quantification of LOCA core damage frequency. In order to quantify it, PSA ETs for LOCA were restructured based on the new break size boundary and the new success criteria obtained from the results of the first part. The AIMS code was used to quantify the LOCA core damage frequency. In this part of our research, target NPPs are KSNP for quantification.

For the first part of the present research, the following conclusions can be drawn:

- In LOCAs of small break sizes (below 1.4 inches), the decay power is well removed by only normal secondary cooling. It means that safety injection is not needed as a success criterion. Considering the conventional PSA of small LOCAs, this result contradicts the widely accepted idea in safety assessment.
- Using only one HPSI pump, the reactor core is properly cooled in LOCAs of break sizes of 0.8 to 9.4 inches. In the conventional PSA ETs, break sizes from 0.8 to 2.0 inches belong to small LOCAs that require the RCS depressurization, and from 6.0 to 9.4 inches belong to large LOCAs that require LPSI as well HPSI. Thus, the capability of HPSI was underestimated in the conventional PSA.
- For the feed and bleed operation, which means HPSI with opening the SDS valve, thermal hydraulics results showed that LOCAs of break sizes below 0.8 inches need the feed and bleed operation. In these cases, an operator should open the SDS valve within 35 minutes after the reactor trip.
- As the major factors that determine the thermal-hydraulics characteristics of LOCA, the RCS pressure and RCS coolant inventory were selected. With these two factors, nine domains were obtained and five groups were identified.

For the second part of the present research, the conclusions can be drawn:

- Based on the thermal-hydraulics results about the new break size boundaries and new success criteria, five new event trees were developed: (1) very small LOCA (Group I, 0.5 to 0.8 inches); (2) small LOCA (Group II, 0.8 to 1.4 inches); (3) medium LOCA (Group III, 1.4 to 9.4 inches); (4) large LOCA (Group IV, 9.4 to 17.8 inches); and (5) very large LOCA (Group V, from 17.8 to 60.0 inches). In terms of the success criteria for each group, the feed and bleed operation is for very small LOCAs, HPSI only is for small and medium LOCAs, normal secondary cooling is for very small and small LOCAs.
- The core damage frequency of new LOCA ETs is 5.80E-07 (/y), which is 12% less than the conventional one. For quantification, the initial frequencies of five groups were estimated by using power law fits with real plant data. The core damage frequency difference between conventional and updated mostly originated from different success criteria of small break size LOCAs, because, in improved ETs, normal secondary cooling only is accepted as a success criterion.

The present study has the following limitations:

- The thermal-hydraulics results were obtained only based on KSNP, which is the most type in South Korea. The same method can be used for other NPP types.
- The uncertainties of several variables were not considered in this research. For example, the flow rate of the HPSI pump has uncertainty and it may affect to the break size boundary. However, it may not have affected the determined success criteria.

In this research, we obtained not only thermal-hydraulics characteristics for entire break size of the LOCA in view of the deterministic safety assessment, but also a more realistic core damage frequency of the LOCAs using updated information. The difference between the results of the present study and the conventional knowledge could be used to modify the current EOP and to design another NPP type.

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