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Evaluation of Post-LOCA Long Term Cooling Performance in Korean Standard Nuclear Power Plants

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Abstract

The post-LOCA long term cooling (LTC) performance of the Korean Standard Nuclear Power Plant (KSNPP) is analyzed for both small break loss-of-coolant accidents (LOCA) and large break LOCA at cold leg. The RELAP5/MOD3.2.2 beta code is used to calculate the LTC sequences based on the LTC plan of the Korean Standard Nuclear Power Plants (KSNPP). A standard input model is developed such that LOCA and the followed LTC sequence can be calculated in a single run for both small break LOCA and large break LOCA. A spectrum of small break LOCA ranging from 0.02 to 0.5 ft^2 of break area and a double-ended guillotine break are analyzed. Through the code calculations, the thermal-hydraulic behavior and the boron behavior are evaluated and the effect of the important action including the safety injection tank (SIT) isolation and the simultaneous injection in LTC procedure is investigated. As a result, it is found that the sufficient margin is available in avoiding the boron precipitation in the core. It is also found that a further specific condition for the SIT isolation action need to be setup and it is recommended that the early initiation of the simultaneous injection be taken for larger break LTC sequences.

Key Words : long term cooling, break spectrum, boron behavior, RELAP5/MOD3.2.2beta

1. Introduction

Long term cooling (LTC) after a loss-of-coolant-accident (LOCA) is defined as a plant cooldown process of the Reactor Coolant System (RCS) from the time when the reactor core was quenched to the time when the plant could be brought into the secured state (i.e., the cold shutdown condition). It was one of the acceptance criteria of the requirements on the emergency core cooling system (ECCS) performance evaluation in light water reactor (LWR) [1].

The important element of the post-LOCA LTC plan of the Korean Standard Nuclear Power Plants (KSNPP) including the UCN Units 3/4 [2] is to discharge steam through the atmospheric dump valves (ADV) in the steam generators (SG) for core decay heat removal and to activate the simultaneous injection to RCS hot legs and cold legs for core flushing flow. The simultaneous injection is attempted to establish the positive net flushing flow against the boil-off in the reactor vessel core. Those manual actions are based on the operator decision on the RCS pressure, which is dependent on the break size. The performance of such a LTC plan was evaluated by analyzing the LTC sequences following SBLOCA and LBLOCA [3]. The analysis was to justify that the core could be maintained at a safe temperature level through the proposed LTC procedure and the precipitation of boric acid in the core region could be sufficiently avoided with a minimum manual action. The analysis method was based on the simple and conservative approach developed by the Combustion Engineering [3]. The methodology was composed of the calculation of the natural circulation flow in the core, the calculation of SG secondary system temperature when ADV are operated, the calculation of primary system depressurization using heat transfer to the secondary system, and the calculation of the boron concentration using the data above. Each calculation was iterated to provide an appropriate data for the proceeding calculations and was based on the conservative assumptions. One of the example is to overestimate the heat transfer to SG secondary side by ignoring the energy discharged through the break flow when calculating the SG secondary system temperature. And then the overestimated secondary side temperature is used as a heat source when calculating the primary side behavior.

Although the proposed LTC evaluation methodology was recognized as a conservative one [4] in prescribing the correct operator action, the plant thermal-hydraulic response was not fully explained by those analyses, thus, total safety margin could not be identified. It was because the evaluation methodology was developed in the early 1970' s, and a realistic calculation of the response of the whole system could not be possible by the technology at that time. Thus, the important result such as RCS pressure versus the break size at 9 hours after accident could be questioned in the viewpoint of its reliability. Also, the effect of the individual action was not realistically considered including the safety injection tank (SIT) isolation and the simultaneous injection incorporated into the LTC plan on RCS thermal-hydraulic response and boron behavior in the core.

The present paper primarily aims to investigate the realistic plant thermal-hydraulic behavior including the boron transport behavior during LTC sequences following SBLOCA and LBLOCA of the KSNPP. Through the analysis, the realistic performance of the current LTC plan, e.g., the required time for the RCS refill to establish the shutdown cooling system (SDC) entry condition and the prevention from core boron concentration, can be evaluated. It also aims to evaluate the effectiveness of the important actions such as SIT isolation and simultaneous injection of the LTC procedure.

For this purpose, realistic long-term calculation was performed for SBLOCA and LBLOCA. In SBLOCA-LTC analysis, a range of break spectrum from 18.6 cm^2 to 465 cm^2 (hereafter, 0.02 ft^2 to 0.5 ft^2) cold leg break area was calculated, while a double-ended cold leg guillotine break was calculated as a representative LBLOCA-LTC sequence. All of the sequences were calculated using the RELAP5/MOD3.2.2 beta code [5], which has an improved capability in the computational time step control that provides a calculational efficiency in this kind of long-term calculation.

2. LTC Plan of KSNPP

In KSNPP, the LTC plan uses either of two procedures depending on the break size [2]. Shutdown cooling system (SDC) is initiated if the break is sufficiently small that successful operation of the SDC assured. For larger break LOCA, simultaneous hot- and cold-leg injection is used to maintain core cooling and boric acid flushing. The operator initiates the appropriate procedure based on the indicated RCS pressure. Figure 1 shows the basic sequence of events and time schedule of the LTC plan.

1) The operator's first action is to initiate cooldown by 1 hour post-LOCA by releasing steam from the SG. Either of the turbine bypass system or ADV can be used.
2) Between 1 and 3 hours post-LOCA, the SIT's are isolated or vented to avoid injecting a large amount of nitrogen gas into the RCS.
3) Between 1 and 4 hours post-LOCA, a pressurizer cooldown is initiated.
4) Between 2 and 3 hours post-LOCA, the HPSI pump discharge is realigned such that the total injection flow is divided about equally between the hot and cold legs.
5) Between 9 to 10 hours after LOCA, if the RCS pressure is above 3.7 MPa (550 psia), the RCS is filled, which ensures that proper suction is available for entering SDC. The RCS cooling continues until the indicated RCS temperature is lower than the SDC entry temperature, 477.6 K (400°F). The HPSI pumps are then throttled until the RCS pressure is reduced to SDC entry condition, 2.79 MPa (410 psia). A prerequisite to throttling or terminating HPSI flow is that the RCS must be in a subcooled condition for the indicated RCS pressure. If the SDC system is inoperable, an alternative method for decay heat removal is the continued use of SG. This method requires the continued availability of auxiliary feedwater and the ADV or the steam bypass valve.
6) If the indicated RCS pressure is below 3.7 MPa (550 psia) at 9 to 10 hours, it implies the break is too large to assure a proper suction for SDC operation. In this event, continued simultaneous injection will cool the core and flush indefinitely.

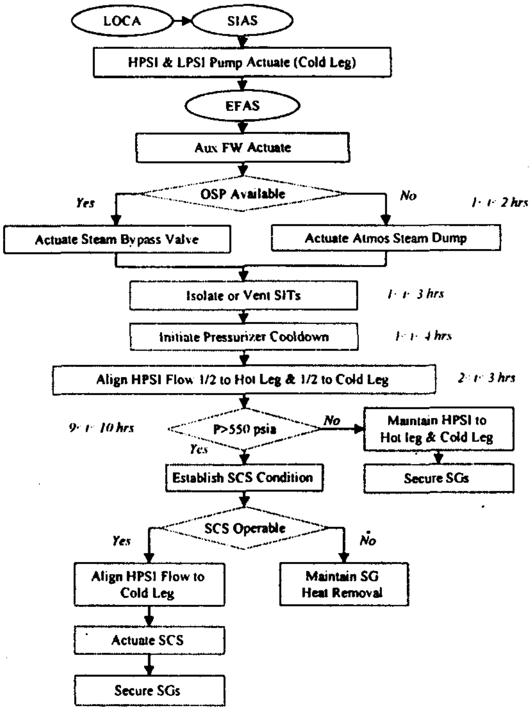

Fig. 1. Long Term Cooling Plan in KSNPP

From the LTC plan explained above, it was found that the realistic performance of the LTC plan should be evaluated and the effect of important manual actions such as the SIT isolation and the initiation of simultaneous injection should be clarified to confirm the effectiveness of the LTC plan.

3. Code and Modeling Scheme

In the present analysis, the RELAP5/MOD3.2.2 beta which was the most improved version of the

Table 1. ECCS Flow Distribution

Items	Broken Loop		Intact Loop (lumped)		
Injection Point	Cold Leg[1)]	Hot Leg	Cold Leg	Hot Leg[2)]	Total[3)]
Before RAS	$Q_H/4 + Q_L/2$	0	$Q_H/2$	0	$Q_H + Q_L$
After RAS	$Q_H/4$	0	$Q_H/2$	0	Q_H
HCSI activated before RAS	$Q_H/8 + Q_L/2$	$Q_H/2$	$Q_H/4$	0	$Q_H + Q_L$
HCSI activated after RAS	$Q_H/8$	$Q_H/2$	$Q_H/4$	0	Q_H

Note 1) No ECCS flow into the broken cold leg, however, the same amount as water injected into the unbroken cold leg was taken into account when calculating the total amount of RWT water injected

2) No ECCS flow into the intact loop hot leg due to the single failure

3) Total flow includes the spilled out water from the broken cold leg

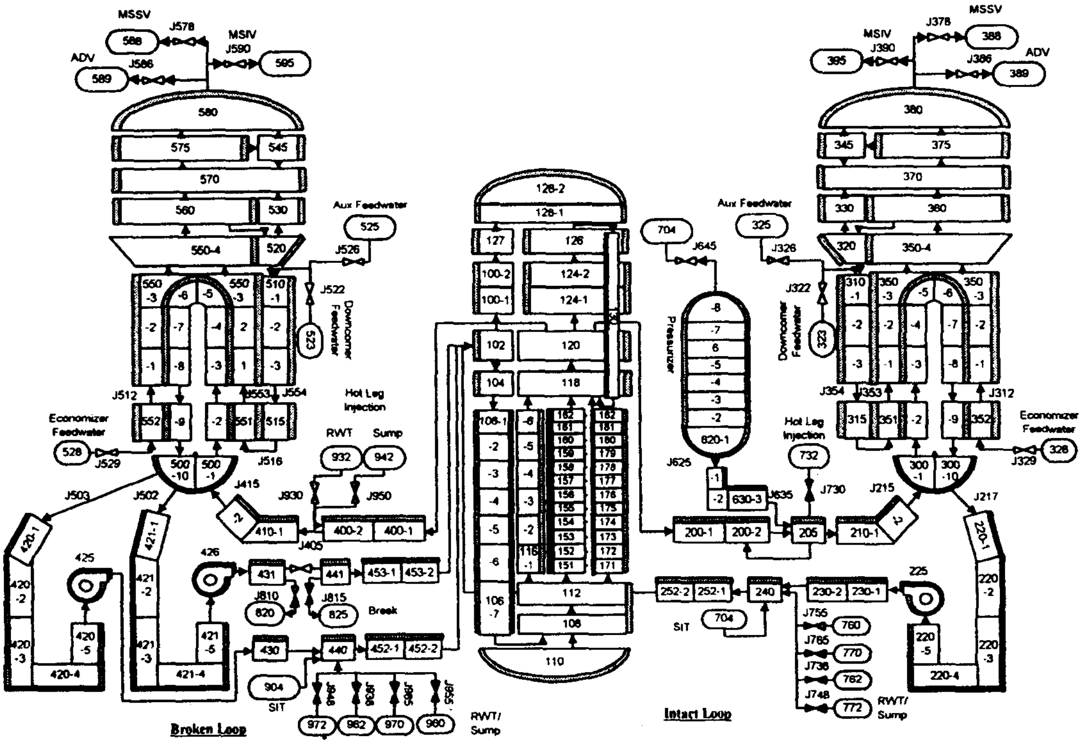

Fig. 2 RELAP5 Nodalization for LTC Analysis of KSNPP

RELAP5/MOD3 code was used. The code has been developed by USNRC as one of the best estimate system thermal-hydraulic analysis code. Its applicability to small break LOCA and various transients was systematically validated for various experimental data [7]. For the large break LOCA, the code predictability was validated including the reflood heat transfer model [8]. The RELAP5/MOD3.2.2 beta also has been some improved features such as Courant time limit based on junction velocity; time step control; flow anormaly reduction; mass error reduction, etc.

It is known that the boron is transported into the reactor core by the ECCS water following the LOCA and that it is precipitated by the coolant boil-off in the core. The behavior is, in nature, three-dimensional two-phase turbulent process, and its prediction needs a sophisticated three-dimensional computational fluid dynamic (CFD) code. However, it was also recognized that the basic process of the boron transport is strongly dependent on the liquid phase transport and the maximum boron concentration could be predicted conservatively by one-dimensional approximation [4]. Therefore, the RELAP5 code is believed to apply to evaluate the boron transport and the maximum boron concentration in the core. Especially, the RELAP5/MOD3.2.2 beta code has a boron transport model based on the improved second-order Gudnov scheme, which will provide more accurate prediction. The improved performance of the scheme was verified with the LOFT L6-6 boron dilution experiment [9].

In the present analysis, LOCA and the proceeding LTC sequence were calculated in a single run. Based on the UCN Units 3/4 geometry, a standard RELAP5 input model was developed, which can be commonly applicable to the SBLOCA-LTC and LBLOCA-LTC. The nodalization diagram can be found in Figure 2. The model consisted of 191 hydrodynamic volumes, 218 junctions, and 212 heat structures. The model includes the reactor vessel, the RCS loops, the reactor coolant pumps (RCP), the SG primary and secondary sides, the pressurizer, the ECCS, the auxiliary feedwater system (AFW), the break valves, etc. Two cold legs at the intact loop were lumped into a single leg with the doubled volume, while those at the broken loop were separately modeled. The reactor vessel core was modeled using two separate channels; average channel and hot channel with area ratio of 50:1. Each channel had twelve axial nodes and was linked with crossflow junctions.

In modeling the ECCS, the Refueling Water Tank (RWT) and the Containment Recirculation Sump (CRS or sump) were separately modeled considering the switch-over of the ECCS water sources and the turning-off the low pressure safety injection (LPSI) pump when the Recirculation Actuation Signal (RAS) occurred. The manual action to initiate the simultaneous injection to hot leg and cold leg (HCSI) was also considered such that the injected water was distributed evenly to the hot and cold legs. Additionally, one train of the ECCS was assumed not available to match the worst single failure criteria, i.e., one emergency diesel generator failure. And the injected water into the cold leg with break was assumed to spilled out to be consistent with the FSAR analysis. Based on these considerations, Table 1 shows the ECCS flow distribution used in the calculation, where Q_H and Q_L are the flow rates from the performance curves of one HPSI pump and LPSI pump, respectively.

The initial core power was assumed to be 102 % of normal power (2871 MWt) with RCS hot leg temperature and cold leg temperature of 601 K (623°F) and 569 K (565°F), respectively. The pressurizer pressure was also assumed as 15.34 MPa (2,255 psia) and total RCS flow rate as 1,530.9 kg/sec (121.5×10^5 lbm/hr). The initial boron concentration of the RCS was 0.85 wt%. The assumed values were based on the FSAR LOCA analysis [2], and the calculated values of the important parameters through the steady state initialization process were well close to the corresponding FSAR data.

The fission product decay heat was considered in a conservative way, i.e., 1.2 times of ANS-73 model [10]. The moderator density coefficient feedback was modeled using a conservative MTC curve at the beginning of life (BOL) core of UCN Units 3/4. The reactor trip was assumed to occur at 10.59 MPa (1,555 psia). Loss of offsite power was assumed to occur coincident with break and not to recover throughout the transient. The safety injection was assumed to initiate at 10.59 MPa (1,555 psia) with time delay of 50 seconds. During the SG cooldown phase, the atmospheric dump valves (ADV) were modeled to cooldown the RCS to 560 K (550°F) within the limit of 37.8 K/hr (100°F/hr) according to emergency operation procedure (EOP) [11]. The AFW was modeled to maintain the SG inventory at 23.5 % wide range water level as a minimum. The main steam safety valves (MSSV) were also modeled to open at 8.6 ~ 9.24 MPa (1,264.7 ~ 1,359 psia) range. The pressurizer cooldown was not considered since it was a non-safety system not to be credited in the analysis and also not modeled in the FSAR analysis.

The RAS was modeled to occur when the RWT water reaches 5 % of the full range. Throughout the transient the boron concentration of the sump was assumed to be 2.5 wt %. This value is the same as the concentration of the RWT. The sump boron concentration may be lower than this value since the discharged coolant was fully mixed and diluted with deborated water in the actual transient. The assumptions of the manual actions are as follows:

1) The initiation of the SG cooldown was initiated at 3,600 seconds (1 hour)
2) The isolation of the SIT was assumed at 3,600 seconds for SBLOCA. For the larger break than a certain break size, the SIT was emptied before 1 hour.
3) The activation of the simultaneous injection was initiated at 7,200 seconds (2 hours). The effect of HCSI timing was also investigated by using 10,800 seconds (3 hours) for SBLOCA. For the LBLOCA, such an investigation was not performed because the core was expected to refill in 2 hours and, thus, the boron behavior was not significantly changed.

LTC sequences following three small cold leg break LOCA and a double ended guillotine cold leg break LOCA were calculated. LTC sequences following the hot leg break LOCAs are not considered. The hot leg breaks are not the limiting cases since a favorable flow path could be established from the ECCS cold leg injection point to the break through the core, the core refill could be effectively achieved, and the low boron concentration might be expected. The break areas are; 18.6 cm^2, 93 cm^2, and 465 cm^2 (0.02 ft^2, 0.1 ft^2, and 0.5 ft^2), respectively. Each calculation was conducted until 50,000 seconds (13.9 hours). And the LTC sequence following the LBLOCA was calculated until 14,400 seconds (4 hours).

4. Result and Discussion

4.1. Basic Thermal-hydraulic Behavior

The calculated thermal-hydraulic behavior during the LTC sequences following SBLOCA and LBLOCA are described for RCS pressure, RCS temperature, and reactor vessel inventory. Figures 3, 4, and 5 show comparisons of the RCS pressures, RCS hot leg temperatures, and reactor vessel water levels, calculated for those LTC sequences, respectively. The sequence of events for the sequences was summarized in Table 2

After the break, the RCS pressure dropped rapidly to the point where the flashing in the system occurs, and then, the depressurization rate was reduced (Figure 3). It was clearly observed in the 0.02 ft^2 break case. For the 0.02 ft^2 break case, the RCS pressure decreased from 3,600 seconds, which due to the steam dump at the SG. Such a SG cooldown operation resulted in RCS pressure oscillation in several times and brought to the RCS temperature into 560 K (550°F) at 2 MPa in 20,000 second. The RCS pressure, after

Table 2. Sequence of Events Time (sec)

Event	0.02 ft^2 Break	0.1 ft^2 Break	0.5 ft^2 Break	Double-ended LBLOCA
Break	0	0	0	0
Max. Core Power	10	---	---	---
Reactor Trip and SIAS	99.4	28	13.2	7.02
SIT Injection Start	4250	760	140	22
Reflood Initiated	---	---	---	35
MSSV open	358	289	---	---
Max. Secondary Pressure	358	289	---	---
HPSI Start	149	78	63	57.02
SIT Exhausted	---	---	2,310	267
LPSI Start	---	22440	1,270	57.02
MSSV Close	3600	294	---	---
Switchover by RAS	39,840	36,310	23,180	6,183
SG Cooldown Start	3,600	3,600	3,600	3,600
Simultaneous Injection	7,200	7,200	7,200	7,200

SG cooldown period, continued to decrease to 1.5 MPa at 40,000 seconds. For the larger breaks, the overall trend are almost similar to 0.02 ft^2 case. Noticeable difference in the figure is during the the SG cooldown phase and loop seal clearing phase. For the LTC sequences having larger breaks, the SG steam dump condition could not be established, which indicated that the initial heat removal through the break was sufficiently large. The break spectrum in which the SG ADV cooldown is effective will be discussed in the later section. The RCS pressure oscillation before 20,000 seconds for 0.5 ft^2 break case was due to loop seal formation and clearing. Such a pressure transient due to the loop seal behavior was also found in 0.1 ft^2 break case during 20,000 ~ 30,000 seconds, although its magnitude was small. The driving force of the loop seal clearing was the increased steam pressure from the core. From this result, it is found that the RCS pressure oscillation due to loop seal behavior become delayed and its amplitude is reduced as the break size decreases.

For the LTC sequence following LBLOCA, the RCS pressure was instantaneously dropped to the near-ambient pressure, thus, there was no effect of the SG and loop seal behavior. Those behaviors were also found in the RCS temperature transient as shown in Figure 4.

Figure 5 shows that the water level in the reactor vessel for the LTC sequences. The level was dropped from the initial level (12.56 m) to a certain value determined by the balance between the break flow and void formation as described in the RCS pressure behavior. After then, the level re-decreased in a rate induced by the break size. For 0.02 ft^2 break case, the level dropped to the minimum level at 800 seconds, afterwards re-increased by the safety injection and the core remained fully-covered during the whole transient. For 0.1 ft^2 and 0.5 ft^2 break cases, the core was partially uncovered at 500 and 1,000 seconds, respectively, however, it was recovered in a short period. The level was maintained higher than 1 m above the active core for a long term. For the LTC sequence following LBLOCA, the level was dropped to lower plenum during 50 seconds and then recovered by water from SIT.

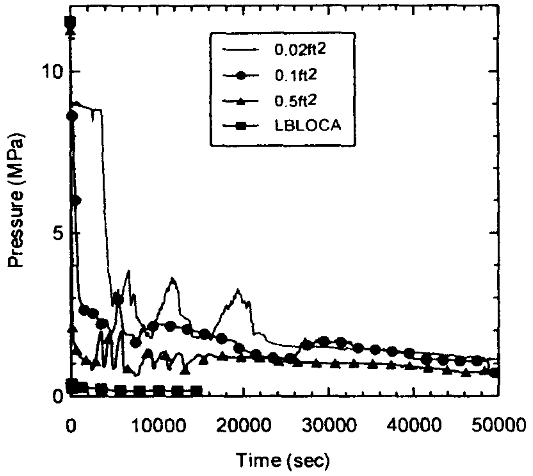

Fig. 3. Comparison of RCS Pressure

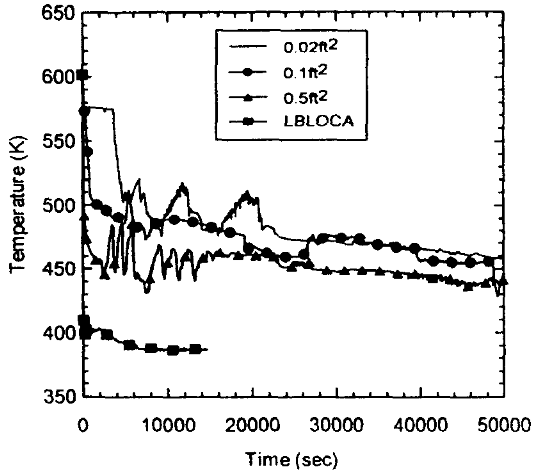

Fig. 4. Comparison of RCS Temperature

The active core was completely refilled in 3500 seconds. The ECCS water source was changed to the containment sump and the LPSI was turned off at 6,200 seconds due to RAS. The vessel level was a little dropped and the top of the active core was slightly uncovered with oscillation. After then, the level was maintained at the top of the core by the injected water to cold leg and hot leg.

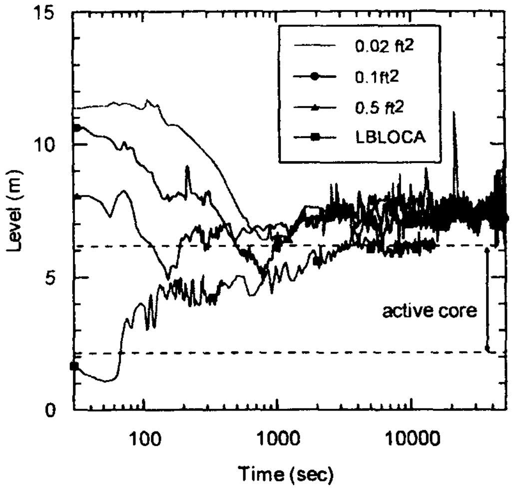

Fig. 5. Comparison of Reactor Vessel Water Level

4.2. Boron Behavior

One of the most important targets of the LTC plan is to avoid the boron precipitation in the core. Figure 6 shows a comparison of a local boron concentration in the core for the given LTC sequences. In the figure the FSAR analysis result [2] for the large break LOCA was also compared. After the break, the highly borated water was delivered to the core from the ECCS and the steam vapor was moved out of the core. Since the boron could not be entrained with the steam flow, the local boron concentration increased by the boil-off process. The oscillatory behavior in boron concentration due to a numerical oscillation during the boiling process. For 0.02 ft^2 break, the boron concentration was less than 6 wt% at the maximum, it decreased from 7,200 seconds by the hot leg injection, and it remained at low level (2.5 wt%). For 0.1 ft^2 and 0.5 ft^2 break cases, the boron concentration initially increased faster and remained high value (10 wt%) for a longer time than the 0.02 ft^2. The significant decrease in the core boron concentration by the simultaneous hot leg injection was not found for those larger breaks. It was believed that the core boil-off rate was higher and maintained for a longer duration than the 0.02 ft^2 break case. However, for a long term, the boron concentration was gradually reduced and remained at a value much lower than the precipitation limit (29 wt%) throughout the transient. The precipitation limit was conservatively selected according to the solubility curve [3].

For LBLOCA-LTC sequence, the boron concentration gradually increased by the ECCS water. At about 6,200 seconds, the boron was started to increase due to the reduced ECCS injection flow by the occurrence of RAS. The simultaneous injection at 7,200 seconds played a role to stop the increase of boron concentration, although its effect was not significant. Based on the trend of the core level and boron behavior up to 15,000 seconds, it was believed that the boron concentration could be further lowered by the continuous simultaneous injection. Also, based on that the maximum boron concentration was 26.5 wt% in the FSAR analysis result, the conservatism of the FSAR methodology could be confirmed

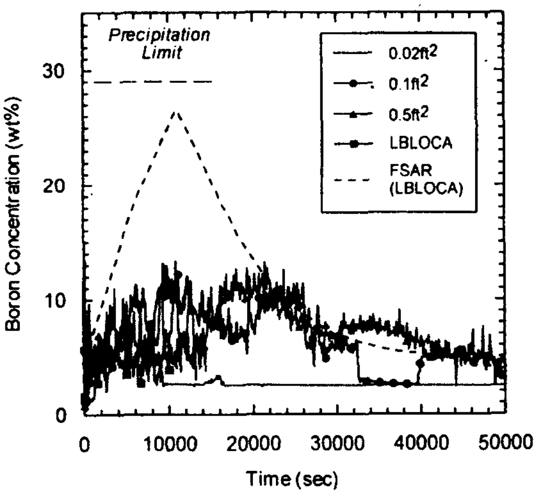

Fig. 6. Comparison of Boron Concentration in the Core

4.3. RCS Refill for SDC Entry Condition

One of the most important targets of the LTC plan is to bring the RCS into the safe condition, i.e., SDC entry condition. The condition should be checked for RCS pressure and temperature (2.79 MPa, 477 K) and the subcooled state for proper SDC suction. The condition for RCS subcooling was not clearly defined in the FSAR, but described as "ΔT_{sub} > 17°F" in the E-01 of the plant EOP [11]. To establish the required subcooling needs a RCS refilling and then re-pressurization by the continuous operation of HPSI pump for a long time after RCS refill. Thus the RCS refill should be evaluated as a check point to the establishment of SDC entry condition.

The LTC plan suggested that the RCS was considered as refilled if the RCS pressure was greater than 3.7 MPa at 9 hours after LOCA in the LTC plan. However the RCS refill condition based on RCS pressure (3.7 MPa) was not established until 50,000 seconds as shown in Figure 3. Figure 7 compares the liquid fractions at the RCS hot leg for the small breaks calculated. The figure showed that the hot leg was refilled at 20,000 seconds (5.6 hours) for 0.02 ft^2 break but not refilled for 0.1 and 0.5 ft^2 breaks. For 0.02 ft^2 break, the calculated RCS pressure at 9 hours (32,400 seconds) was less than 3.7 MPa while that in the FSAR analysis was 1 MPa after RCS refill. It indicated that the additional re-pressurization should be provided to meet the refill criteria in the LTC plan and that the criterion was conservatively developed. The RCS refill time for 0.02 ft^2 break was shorter than the FSAR analysis (6.7 hours) [2], thus, the conservatism of the FSAR analysis result could be confirmed. The total time required to the SDC entry condition will be extended due to re-pressurization to the subcooled

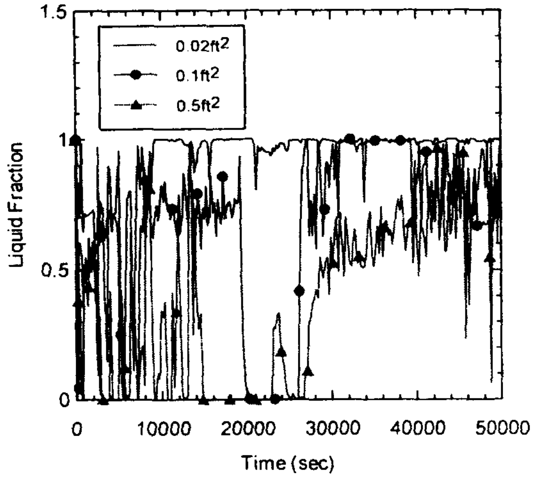

Fig. 7 Comparison of Hot Leg Liquid Fraction

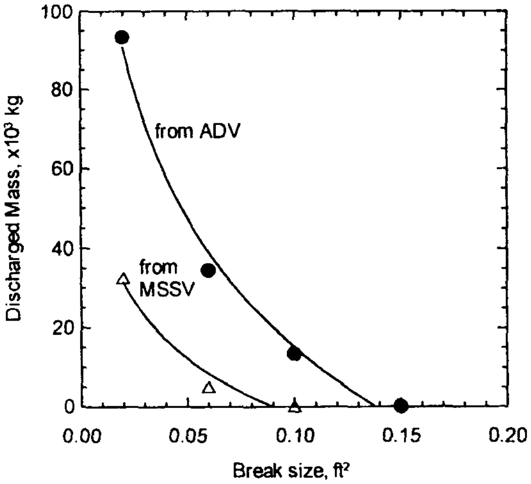

Fig. 8 Comparison of SG Discharged Mass

condition.

4.4. Recirculation Actuation Signal

The recirculation actuation signal (RAS) was calculated to occur at 23,180, 36,310, and 39,840 seconds (6.4, 10.1, and 11.1 hours) for 0.05 ft^2, 0.1 ft^2, and 0.02 ft^2 breaks, respectively. For the large break LTC sequences, it occurred at 6,200 seconds. As mentioned above, the flow rate of the ECCS is reduced by turning off the LPSI pumps, however, its effect was not significant for SBLOCA-LTC sequences investigated, since the RCS pressure was still higher than LPSI pump shutoff pressure (1.4 MPa). For the LBLOCA-LTC sequence, the core refilling was delayed and thus the core boron concentration was a little increased by the RAS.

4.5. Effective Range of the SG Cooldown

In the LTC plan, the SG was used to cooldown the RCS by opening the ADV. Also the SG main steam safety valve (MSSV) was opened to discharge the excessive steam for small breaks since the RCS can be a heat source to the SG. The range of break spectrum where the SG ADV operation was effective in RCS cooldown was identified by the present calculation. Figure 8 shows the discharged steam mass from the SGs versus break area. The smaller amount discharge was found for the larger break. And it was found that the MSSV and ADV could not contribute to RCS cooldown for the breaks larger than 0.06 ft^2 and 0.1 ft^2, respectively.

4.6. Effect of SIT Isolation

As previously mentioned, the isolation or vent of SIT was requested to avoid the injection of noncondensible gas into RCS. The LTC plan specified this manual action should be taken in 1 ~ 3 hours after LOCA. However, the specific condition on SIT isolation such as RCS pressure was not described in the plan. It was specified in the applicable EOP of the plant [11] that the SIT isolation should be taken if the RCS pressure is less than 2.55 MPa after the RAS. In the present

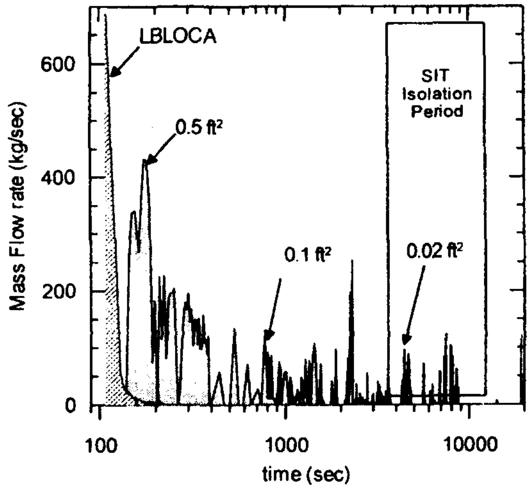

Fig. 9. Comparison of SIT Injection Flow

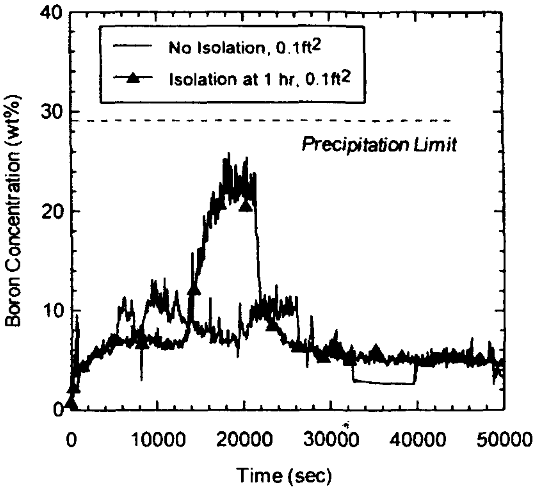

Fig. 10. Effect of SIT Isolation for 0.1 ft^2 Break

study, it was evaluated if any specific condition should be determined by investigating the effect of SIT isolation at one hour after LOCA on the RCS thermal-hydraulic response.

Figure 9 shows a comparison of the injected mass flow rate from the SIT for those LTC sequences. For LBLOCA-LTC case and 0.5 ft^2 break LTC case, the SIT injection was already terminated at 200 seconds and 2,000 seconds, respectively, while for 0.02 ft^2 break case, the SIT injection was started at 3,500 seconds. Thus, for a certain range of break spectrum, the ECCS flow could be significantly reduced by one-hour-isolation. And it may result in insufficient core cooling.

Figure 10, as one of the example, compares the core boron concentration for 0.1 ft^2 break case between the case of SIT isolation at one hour and case of no isolation. The boron concentration with SIT was higher than that without SIT after 3600 seconds, however, this trend was turned over from 13000 to 22000 seconds. It was believed that such an increase of core boron concentration was due to the increase in core boil-off rate. It was obviously due to the delay in loop seal clearing caused by reduction of ECCS flow. Therefore, such an isolation of SIT at one hour post-LOCA could be worse for a certain range of break spectrum, although the maximum value of boron concentration was still less than the precipitation limit. From this result, it can be stated that more specific condition for the SIT isolation in the LTC plan should be described considering the break spectrum behavior.

4.7. Effect of the Simultaneous Injection Time

The simultaneous injection to hot leg and cold leg at 2 ~ 3 hours after LOCA was requested in the LTC plan. To evaluate the effect of the simultaneous injection on the LTC performance, additional calculation was conducted for the case of the simultaneous injection at 3 hours. Figure 11 compares the core boron concentration between 2-hour-case and 3-hour-case for 0.02 ft^2 break. One can find that the boron concentration could be lowered from the time initiating the simultaneous injection for both cases. And it is found that the maximum value was not much

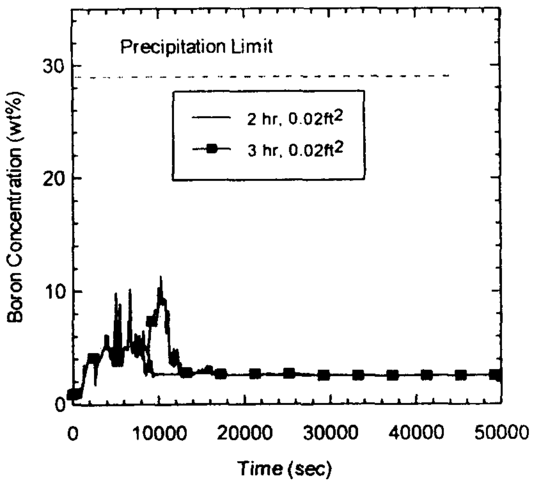

Fig. 11. Effect of Simultaneous Injection for 0.02 ft^2 Break

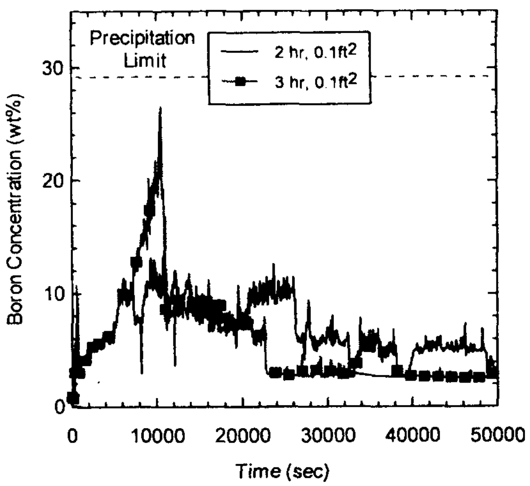

Fig. 12. Effect of Simultaneous Injection for 0.1 ft^2 Break

increased in spite of the delayed simultaneous injection. In the Figure 12, however, it can be shown that the core boron concentration could be significantly increased for 0.1 ft^2 break if the simultaneous injection was delayed, although the maximum value was still less than the limit. It was due to the increased boil-off rate in the core for larger break sizes. Therefore, it was recommended that the simultaneous injection should be initiated as early as possible after LOCA for larger size of break.

5. Conclusions

The post-LOCA long term cooling (LTC) performance of the Korean Standard Nuclear Power Plant (KSNPP) was analyzed for both small break LOCA and large break LOCA. The RELAP5/MOD3.2.2 beta code was used to calculate the LTC sequences based on the LTC plan of the KSNPP. A standard input model was developed such that LOCA and the followed LTC sequence can be calculated in a single run for both small break LOCA and large break LOCA. A spectrum of small break LOCA ranging from 0.02 to 0.5 ft^2 break and a double-ended guillotine break were analyzed. Through the code calculations, the basic thermal-hydraulic behavior and the boron behavior were investigated and the effect of the important manual actions including the SIT isolation and the simultaneous injection was investigated. The following conclusions are obtained:

1) Through the realistic calculation, the thermal-hydraulic behavior during LTC sequence was analyzed and the effect of the important manual actions including the SG cooldown operation, the SIT isolation, and the simultaneous injection were evaluated using the RELAP5/MOD3.2.2 beta code and the current modeling scheme.
2) The RCS can be refilled at 5.6 hours after 0.02 ft^2 break LOCA. There was a sufficient margin in avoiding the core boron precipitation for all LTC sequences with small break and large break.
3) From the calculation, it was found that the SG was effective in cooling down the RCS up to the break size of 0.1 ft^2.

4) Further specific conditions on the SIT isolation in LTC plan should be described considering the break spectrum behavior, since the early SIT isolation could lead to undesired increase of core boron concentration for a certain range of break.
5) The two-hour-initiation of the simultaneous injection is recommended for the LTC sequences following larger break LOCA, since the delayed initiation of the simultaneous injection could lead to undesired increase of core boron concentration.

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