Proceedings of Korean Nuclear Society Spring Meeting
Pohang, Korea, May 1999

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 LOCA and large break LOCA. The RELAP5/MOD3.2.2 code is used to calculate the LTC sequences based on the LTC plan of the 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 manual action including the safety injection tank isolation in LTC procedure is investigated.

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 requirements in the acceptance criteria on the emergency core cooling system (ECCS) performance in light water reactor (LWR) [1].

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) and to activate the simultaneous injection to RCS hot legs and cold legs. The simultaneous injection was attempted to establish the flushing flow against the boil-off in the reactor vessel core. Those manual actions were based on the operator decision depending on the break size. The performance of such a LTC plan was evaluated by analyzing the plant-specific LTC sequences following SBLOCA and LBLOCA [3]. The objective of the analysis is to justify that the proposed LTC procedure can maintain the core at a safe temperature level and can be sufficient to avoid the precipitation of boric acid in the core region with a minimum manual action based on the reasonable decision. The analysis method was based the simple and conservative approach developed by CE [3].

Although the proposed LTC evaluation methodology was recognized as a conservative one [4] for prescribing the correct operator action, the effectiveness of the LTC procedure and the safety margin relating the plant thermal-hydraulic response have not been fully explained. It was due that the analysis result obtained from the simple conservative method was based on the most limiting case. The effectiveness of SG atmospheric dump and the effects of safety injection tank (SIT) isolation, of ECCS recirculation actuation, and of the simultaneous injection on RCS thermal-hydraulic response and boric acid behavior were not fully understood.

The present paper aims to investigate the plant thermal-hydraulic behavior and the boron behavior during LTC sequences following SBLOCA and LBLOCA of the KSNPP and to evaluate the effect of the important action including SIT isolation of the LTC procedure.

For this purpose, a realistic long-term calculation was performed for SBLOCA and LBLOCA. In SBLOCA-LTC analysis, a range of break spectrum from 0.02 ft^2 to 0.5 ft^2 cold leg break area was calculated, while a double-ended cold leg guillotine break was simulated as a representative LBLOCA-LTC sequence. All of the sequences were calculated by the RELAP5/MOD3.2.2 code [5], which has an improved capability in the computational time step control to be effective in this kind of long-term calculation. The applicability of the code to the thermal-hydraulic phenomena of the LTC scenario was demonstrated by the author's previous work [6].

A standard plant model was developed such that the response of the safety system can be automatically simulated including reactor trip, safety injection actuation signal (SIAS), recirculation actuation signal (RAS), etc.

2. Code and Modeling Scheme

In the present analysis, the RELAP5/MOD3.2.2, the most recent version of the RELAP5/MOD3 code, was used. The code has been developed as one of the best estimate system thermal-hydraulic analysis code, its applicability to small break LOCA and various transients was systematically verified for various experimental data [7]. For the large break LOCA, the code predictability was verified including the reflood heat transfer model [8]. The RELAP5/MOD3.2.2 also has some improved features including Courant time limit based on junction velocity; time step control; flow anormaly reduction; mass error reduction, etc. In addition, the code has a boron transport model based on the improved first-order Gudnov scheme, which was partially verified during the developmental assessment for LOFT L6-6 boron dilution experiment [9].

In the present analysis, the LOCA and the proceeding LTC sequence was calculated in a single run. Based on the UCN Units 3/4 geometry, a standard RELAP5 input model was developed for analyzing thermal-hydraulic transient during LTC process, which can be commonly applied to the SBLOCA-LTC and LBLOCA-LTC. The nodalization diagram can be found in the previous paper [6]. 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 sides 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 with 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 effect of the switch-over of the ECCS water sources and especially the turning-off the low pressure safety injection (LPSI) pump when the 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 legs 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 breaks was assumed to spilled out to be consistent with the FSAR analysis. Based on those considerations, Table 1 shows the ECCS flow distribution used in the calculation, where Q_H and Q_L are flow rates from the performance curves of HPSI pump and LPSI pump, respectively.

Table 1. ECCS Flow Distribution

Items	Broken Loop		Intact Loop (lumped) 2)		
Injection Point	Cold Leg 1)	Hot Leg	Cold Leg	Hot Leg	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	$Q_H/8 + Q_L/4$	$Q_H/2$	$Q_H/4$	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 included the spilled out water from the broken cold leg

The initial core power was assumed to be 102 % of normal power (2871 MWt) under RCS hot leg temperature and cold leg temperature of 623°F and 565°F, respectively. The pressurizer pressure was also assumed as 2255 psia and total RCS flow rate as 121.5 x 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 corresponded FSAR data.

The fission product decay heat was considered by a conservative way, i.e., 1.2 times of ANS-73 model [10]. The moderator temperature coefficient (MTC) feedback was modeled with a conservative MTC curve at the begin of life (BOL) core of UCN Units 3/4. The reactor trip was assumed to occur at 1555 psia. Loss of offsite power was assumed to occur coincident with break and not to recover throughout the transient. The turbine trip following the reactor trip was assumed with 3 seconds delay. The safety injection was assumed to initiate at 1555 psia with time delay of 50 seconds. The During the SG cooldown phase, the atmospheric dump valves (ADV) were modeled to cooldown the RCS to 550°F within the limit of 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 1264.7 ~ 1359 psia range. The RAS was modeled to occur when the RWT water reaches 10 % of the full range. Throughout the transient the boron concentration of the sump was assumed to be constant value as same as that in RWT, i.e., 2.5 wt %. The sump boron concentration may be lower than this value in real situation since the discharged coolant was fully mixed and diluted with deborated water.

In the all LTC sequences following the LOCA, the following manual actions were used:

1) The manual action to initiate the SG cooldown at 3600 seconds (1 hour)
2) The manual action to isolate the SITs was not simulated. However, its effect was investigated by stopping the SIT flow at 3600 seconds for SBLOCA.
3) The manual action to activate HCSI at 7200 seconds (2 hours). The effect of HCSI timing was also investigated by using 10800 seconds (3 hours) for SBLOCA.

3. Result and Discussion

3.1 SBLOCA Long Term Cooling Performance

Three cold leg break SBLOCA-LTC events were calculated; 0.02 ft^2, 0.1 ft^2, and 0.5 ft^2. Each calculation was conducted until 50,000 seconds (13.9 hours)

Thermal-hydraulic Behavior

Figures 1, 2, and 3 show comparisons of the RCS pressure, RCS hot leg temperature, and RCS hot leg liquid fraction, for three events, respectively. After break, the RCS pressure dropped rapidly to the point that the break started to be voided. And then, the depressurization rate was reduced substantially in the 0.02 ft^2 break case, but not in larger break cases. For the 0.02 ft^2 break case, the SG cooldown was activated at 1 hour, which effectively depressurized the RCS, while for larger breaks, the SG steam dump condition was not established, which indicated that the initial heat removal through the break was sufficiently large. The initiation of the simultaneous injection at 7200 seconds and the switch-over of ECCS source on RAS did not show a significant effect on pressure behavior. The RAS was calculated to occur at 23180, 36310, and 39840 seconds (6.4, 10.1, and 11.1 hours) for 0.02 ft^2, 0.1 ft^2, and 0.5 ft^2 break, respectively. The RCS hot leg temperatures showed a similar behavior to RCS pressure.

The hot leg liquid fractions in Fig. 3 show a complex behavior. The hot leg was rapidly voided by break, and then recovered by ECCS water injection with oscillation. Such an oscillation was related to the repeated process of loop seal formation and clearing, as a result, the hot leg was voided again at 20000 and 12000 seconds for 0.1 ft^2 and 0.5 ft^2 breaks, respectively. And the hot leg remained at empty state during more than one hour. However, the hot leg was eventually refilled by the ECCS water at 10000 seconds (2.7 hours) for 0.02 ft^2 break, while not refilled until 50000 seconds for 0.1 ft^2, and 0.5 ft^2 break. From those results, it was found that the entry condition of shutdown cooling system (2.7 MPa, 477 K, and the hot leg refilling) can be achieved in 30000 seconds (8.3 hours) for 0.02 ft^2 break. However, the entry condition is expected to achieve by the further cooldown process for larger breaks.

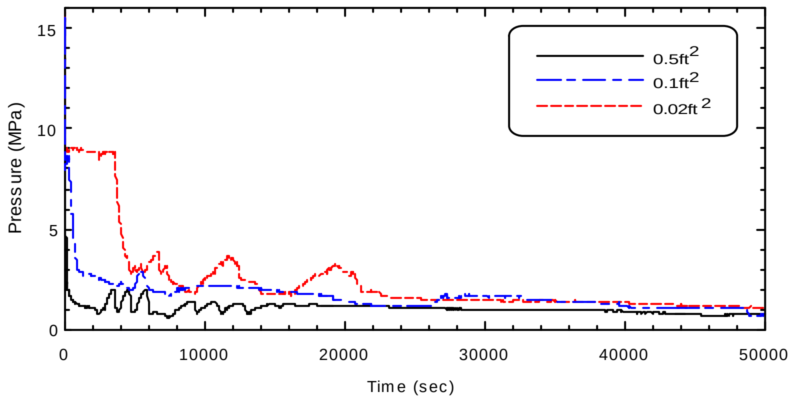

Fig. 1 RCS Pressure for SBLOCA-LTC

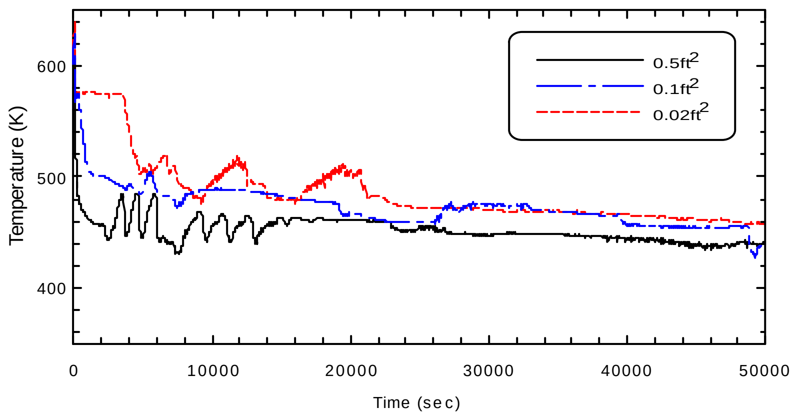

Fig. 2 RCS Hot Leg Temperature for SBLOCA-LTC

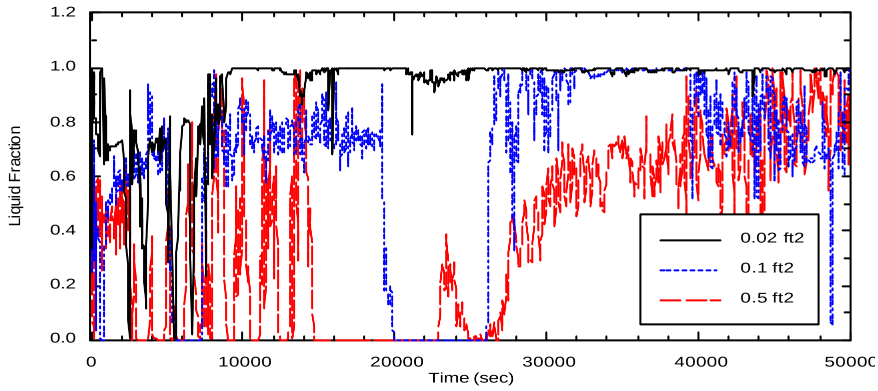

Fig. 3 Hot Leg Liquid Fraction for SBLOCA-LTC

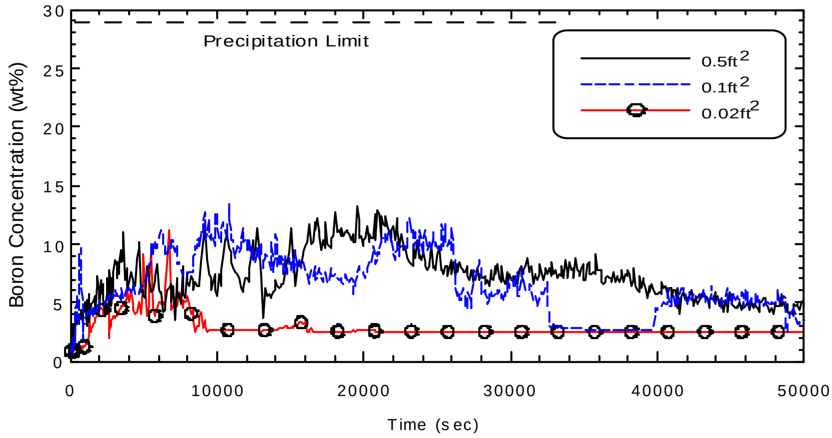

Fig. 4 Boron Concentration for SBLOCA-LTC

Boron Behavior

Fig. 4 shows a comparison of boron concentration in the core for three breaks. After break, the boron concentration increased with oscillation, which was due to the borated water injection and the boil-off in the core. For 0.02 ft^2 break, it can be found the boron concentration decreased from 7200 seconds by the hot leg injection and remained at low level. Such an effect of hot leg injection was not significant for larger breaks. It was believed due to the higher core boil-off rate induced by lower RCS pressure for the larger breaks. 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 for all the break cases.

Effectiveness of 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) can be opened to discharge the excessive steam for the small break since the RCS can be a heat source to the SG. To investigate effectiveness of those SG heat removal capabilities, some additional calculations with varying the break area were attempted. Fig. 5 shows the discharged steam mass from the SGs versus break area. The smaller discharge was found as the larger break. And the MSSV and ADV could not contribute to RCS cooldown for the breaks larger than 0.1 ft^2 and 0.15 ft^2, respectively.

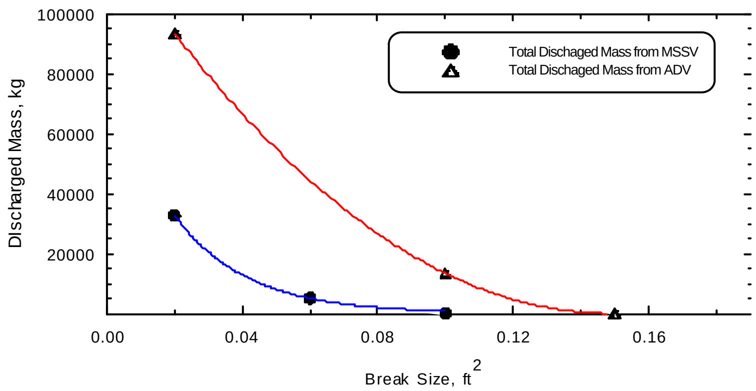

Fig. 5 Effectiveness of SG Cooldown

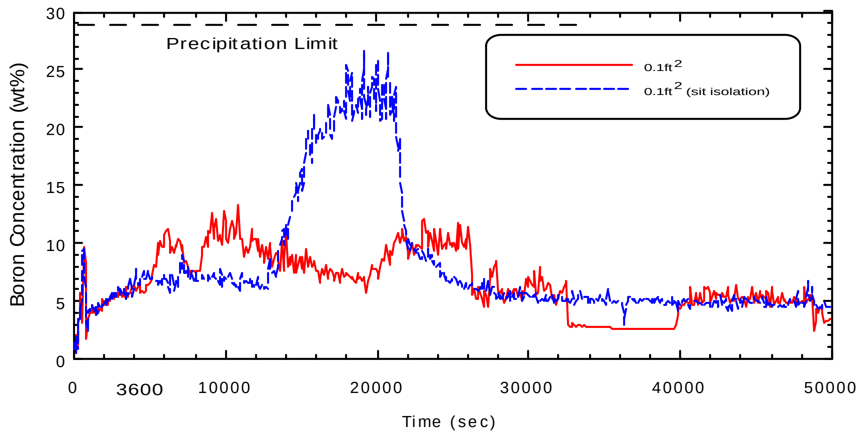

Fig. 6 Effect of SIT Isolation for SBLOCA-LTC

Effect of SIT Isolation

As previously mentioned, all the SBLOCA-LTC calculations were performed with the passive injection from the SIT, which was based on the fact that no specific condition on SIT isolation except time was described in FSAR. Additional calculation was conducted for the 0.1 ft^2 break, to find out the effect of the SIT isolation. This manual action was assumed at one hour after LOCA. Fig. 6 compares the core boron concentration between two cases. The boron concentration of the case using the SIT was higher than that of the case with no SIT after 3600 seconds, however, this trend was turned over from 13000 to 22000 seconds. From this comparison, one can find that the initial SIT injection played a role to increase the boron concentration and that the boron concentration in the case without SIT increased by strong steam pressure over the loop seal, which was caused by no further cooldown from the SIT. From this result, it can be stated that more specific condition on the SIT isolation in LTC plan should be described considering the break spectrum behavior

Effect of the Simultaneous Injection Initiation Time

As previously mentioned, all the SBLOCA-LTC calculations were performed with the hot leg injection at two hours. In the LTC plan of the FSAR, this manual action can be taken at two or three hours after LOCA. Additional calculation was conducted using three hours for the simultaneous injection initiation time for 0.02 ft^2 break. Fig. 7 compares the core boron concentration between two cases. One can find that the boron concentration of each case decreased at each injection time with the almost same peak value. It can be stated that the manual action time for the simultaneous injection has little effect on boron behavior for the small break.

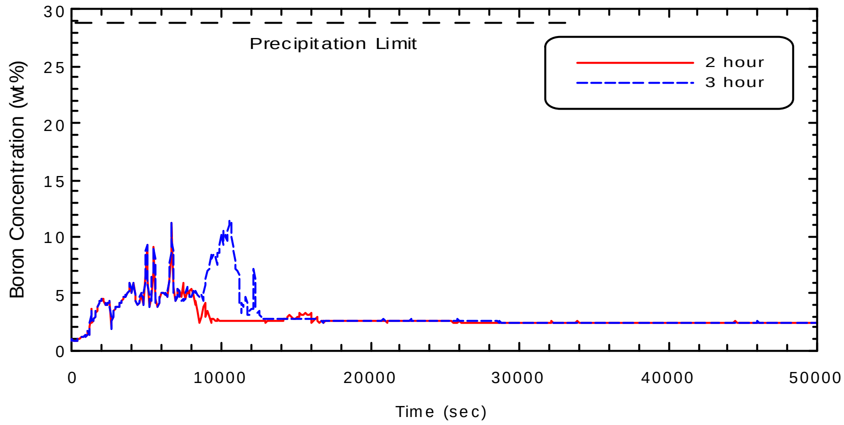

Fig. 7 Effect of Hot Leg Injection Time for SBLOCA-LTC

3.2 LBLOCA Long Term Cooling Performance

A long term cooling sequence following the double-ended cold leg guillotine break LOCA was calculated until 15000 seconds (4.17 hours).

Thermal-hydraulic Behavior

Fig 8 shows a behavior of RCS pressure and the SG secondary side pressure. After break open the RCS pressure rapidly dropped to a low level. The decreasing rate of the SG secondary side pressure was lower than that of the RCS pressure. Accordingly, the RCS pressure was lower than that of the SG pressure, during some period. At about 3000 seconds, the primary pressure was almost close to the secondary side pressure, and the heat balance between RCS and SG was achieved. This pressure level continued for a long time. As discussed earlier, the manual action to open ADV to cooldown the RCS can be taken at 3600 seconds, however, such an action was not effective since the SG pressure was too low to be lowered by opening ADV. The simultaneous injection both to hot leg and cold leg attempted at 7200 seconds has changed the injection flow rate to RCS cold legs and hot legs. The recirculation actuation signal (RAS) automatically occurred at 6200 seconds. It is found that those manual and automatic actions also did not have significant impact on pressure response.

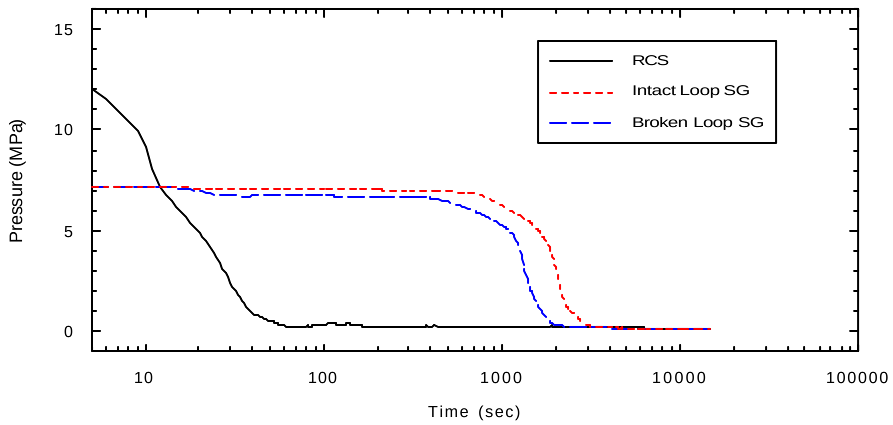

Fig. 8 Primary System Pressure and SG Secondary System Pressure for LBLOCA-LTC

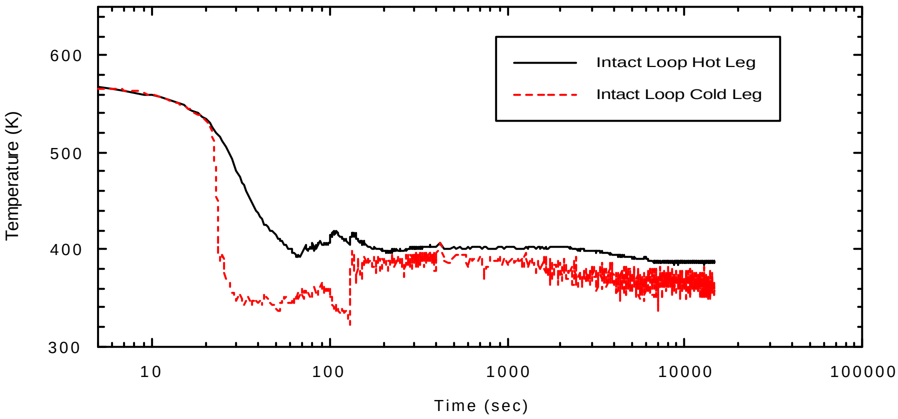

Fig. 9. Intact Loop Coolant Temperature for LBLOCA-LTC

Fig. 9 shows a thermal response at the intact loop hot leg and cold leg. After break open the both temperature decreased by the reactor trip due to low pressurizer pressure and rapid blowdown, and energy discharge through the break. At the time of SIT injection (25 sec) the cold leg temperature drastically decreased by mixing with cold SIT water, and then increased a little due to termination of SIT injection. Afterwards. a slow decrease of temperature was followed at the saturation state.

Fig. 10 shows a fuel cladding temperature during the transient. The peak caldding temperature occurred at 60 seconds and the quenched until 400 seconds. After then, the clad temperature was maintained at a sufficiently low level for a long time.

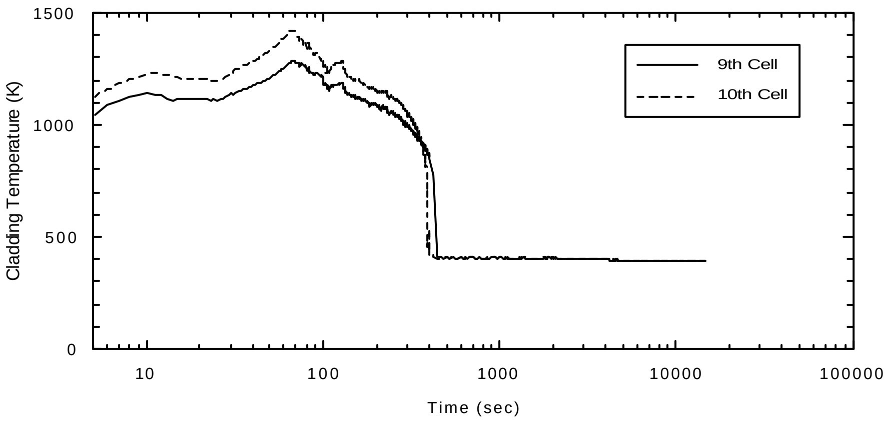

Fig. 10 Cladding Temperatures for LBLOCA-LTC

Two curves in Fig. 11 presented collapsed water levels at the core and downcomer of the reactor vessel, respectively. After break, both levels decreased and the entire core was emptied until 60 seconds. Although the SIT's were started to inject from 20 seconds, the injected water was bypassed out through the break until 60 seconds. After that, the SIT water refilled the downcomer first and then the core. And then, the LPSI water contribute the core refill up to 6200 seconds when RAS was activated. At that RAS timing, the gradual increase of core water level was stopped by the RAS which turned off the LPSI pump and, as a result, the core level decreased a little until it was compensated by a HPSI pump. Eventually the water level was recovered to the top of the active core. It was shown that the core level behavior was not significantly changed by the simultaneous injection since the total amount of injected water during the recirculation mode was quite small when compared to the cold leg injection mode.

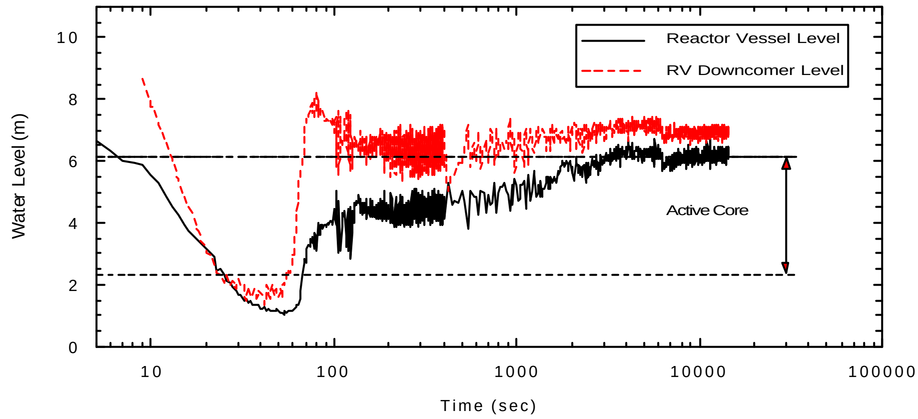

Fig. 11 Core Level and Dowoncomer Level of Reactor Vessel

Boron Behavior

Fig 12 shows concentrations of boric acid at the average core channel and hot core channel of the reactor vessel. The figure shows that the core boron concentration was much lower than the precipitation limit (29 wt %) throughout the transient. The peak of boron concentration at 10 seconds was due to a rapid depletion of water by opening the break. Afterward, the boron concentration was gradually increased by the highly-borated water injected from HPSI and LPSI. As the reactor vessel core level started to increase from 1000 seconds, as shown in the Fig. 11, the boron concentration was slightly lowered. At about 6200 seconds, the boron was started to re-accumulate due to the occurrence of RAS, which deactivated LPSI pump, reduced ECCS injection flow, and resulted in the core level decrease. The simultaneous injection at 7200 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 15000 seconds, it was believed that the boron concentration should be further lowered by the continuous simultaneous injection.

Fig 13 shows a comparison of core flushing flow between the present calculation and FSAR analysis. The core flushing flow was defined as a difference between the hot leg injection flow rate and the core boil-off rate. In the FSAR analysis the simultaneous injection was conservatively assumed to actuated at 3 hours after LOCA and the hot leg injection flow rate to be 302 gpm. As a result, 20~80 gpm of water flow could contribute to core flushing until 6 hours in FSAR analysis, where the core boil-off rate was calculated simply by using the Wallis' correlation [12]. The boil-off rate predicted from the present analysis was close to the FSAR data, the calculated core flushing flow was more than 150 gpm. As a result, the conservatism in FSAR analysis can be confirmed.

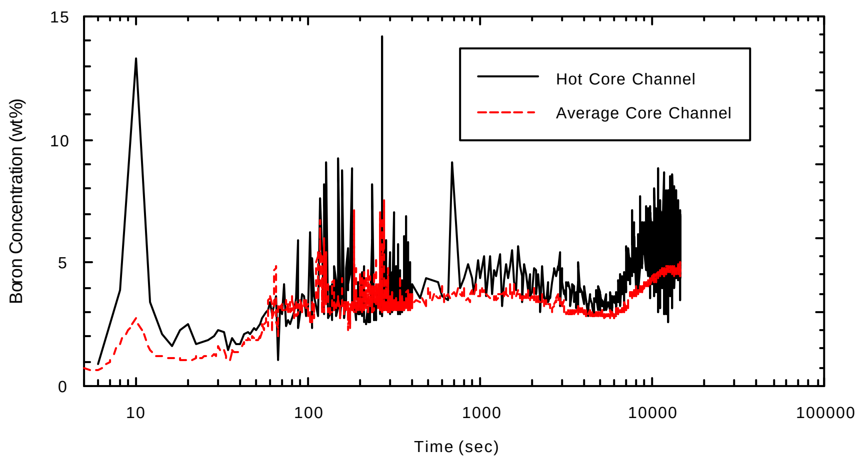

Fig. 12 Boron Concentration in the Core for LBLOCA-LTC

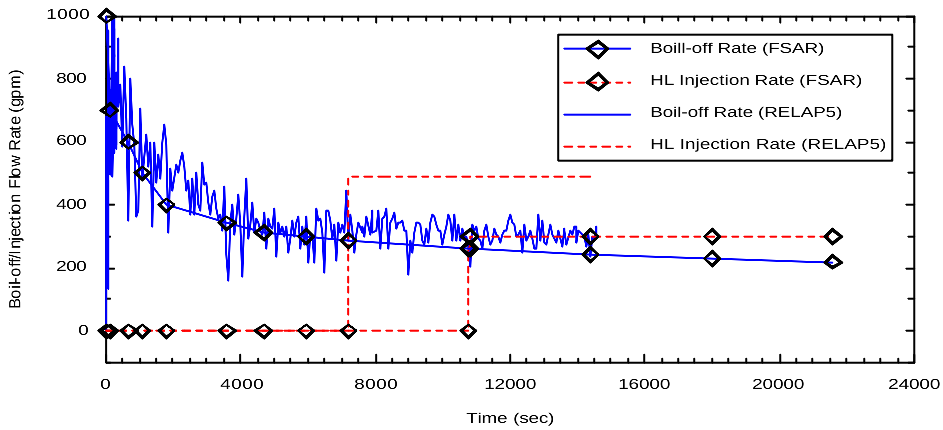

Fig. 13 Core Flushing Flow and Boil-off Rate for LBLOCA-LTC

Fig. 14 Estimated Boron Concentration of the Sump for LBLOCA-LTC

4. 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 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 of break area and a double-ended guillotine break were analyzed. Through the code calculations, the thermal-hydraulic behavior and the boron behavior were evaluated and the effect of the important manual action including SIT isolation was investigated. The following conclusions are obtained:

1) Through the realistic calculation, the thermal–hydraulic behavior during LTC sequence can be described and the effect of the important manual action including SG cooldown and simultaneous injection was evaluated. The entry condition to the shutdown cooling system was established at 8.3 hours after LOCA for 0.02 ft^2 break. There was a sufficient margin in avoiding the core boron precipitation for both small and large break LOCA.
2) From the sensitivity calculation, it was found that the SG was effective in cooling down the RCS up to the break size of 0.1 ft^2. The isolation of the SIT could cease the cooldown capability of SIT and increase the core boron concentration for the LTC sequence following small break LOCA. Thus, more specific condition on the SIT isolation in LTC plan should be described considering the break spectrum behavior. And the boron behavior was not affected by the action time to initiate the simultaneous injection.

References

[1] USNRC, Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Power Reactors, Code of Federal Regulations Part 10 Section 50.46, August 1988.
[2] KEPCO, Final Safety Analysis Report, Ulchin Units 3 & 4, September 1994.
[3] Combustion Engineering Inc., Post-LOCA Long Term Cooling Evaluation Model, CENPD-254-P-A, June 1980 (Proprietary).
[4] USNRC, Letter to A.E.Scherer (CE), Staff Evaluation of Topical Report CENPD-254-P, July 1979.

[5] The Thermal Hydraulics Group, RELAP5/MOD3 Code Manual, RELAP5/MOD3.2.2Beta, Formerly NUREG/CR-5535, Scientech Inc., March 1998.

[6] Young S. Bang, et. al., An Application of RELAP5/MOD3 to the Post-LOCA Long Term Cooling Performance Evaluation, Proceedings of KNS Autumn Meeting, Seoul, Korea, October 1998

[7] Richard R. Schultz, International Code Assessments and Applications Program: Summary of Code Assessment Studies Concerning RELAP5/MOD2, RELAP5/MOD3, and TRAC-B, NUREG/IA-0088, September 1992.

[8] G.A. Mortensen, RELAP5/3.2.2Beta, Presented at the 1998 CAMP Meeting, TAEA, Turkey, June 1998.

[9] Gary W. Johnsen, RELAP5 Development Status, Presented at the Sixth CAMP Meeting, VTT, Finland, May 1995.

[10] ANS Standards Committee, Proposed American Nuclear Standards-Decay Energy Release Following Shutdown of Uranium Fueled Thermal Reactors, Approved by Subcommittee, ANS-51.1, October 1971.

[11] KEPCO, Loss of Coolant Accident, Emergency Operation Procedure, E-01, June 1994.

[12] G.B. Wallis, One-Dimensional Two-Phase Flow, McGraw-Hill, 1969.