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Loss of Coolant Accident Analysis During Shutdown Operation of YGN Units 3/4

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Abstract

A thermal-hydraulic analysis is conducted on the loss-of-coolant-accident (LOCA) during shutdown operation of YGN Units 3/4. Based on the review of plant-specific characteristics of YGN Units 3/4 in design and operation, a set of analysis cases is determined, and predicted by the RELAP5/MOD3.2 code during LOCA in the hot-standby mode. The evaluated thermal-hydraulic phenomena are blowdown, break flow, inventory distribution, natural circulation, and core thermal response. The difference in thermal-hydraulic behavior of LOCA at shutolown condition from that of LOCA at full power is identified as depressurization rate, the delay in peak natural circulation timing and the loop seal clearing (LSC) timing. In addition, the effect of high pressure safety injection (HPSI) on plant response is also evaluated. The break spectrum analysis shows that the critical break size can be between 1 % to 2 % of cold leg area, and that the available operator action time for the SI actuation and the margin in the peak clad temperature (PCT) could be reduced when considering uncertainties of the present RELAP5 calculation.

1. Introduction

The accident during shutdown operation of nuclear power plant (NPP), in contrast with that during full power operation, has been recently emphasized due to its potential for leading to a severe condition because the various systems and equipment may be unavailable during shutdown operation modes. The previous probabilistic risk assessments (PRA) studies conducted under shutdown condition [1] showed that some of the shutdown events may contribute significantly to the total risk.

In reality, there were some events occurred during shutdown modes such as the draindown event of the Wolf Creek Unit of September 1994, the event of the Braidwood Unit 2 of March 1990, etc., [2]. Those events indicated there has existed a substantial possibility of loss of coolant accident (LOCA) during shutdown operation. It was also found that an operator action to activate safety injection (SI) should be taken in a certain time or the automatic SI should be available at the operating mode 3(hot-standby) and mode 4(hot-shutdown) to mitigate the consequence of small break LOCA, from the previous study on adequacy of emergency core cooling system (ECCS) design [3]. Such an automatic SI actuation at modes 3 and 4 was also incorporated in the System 80+ design [4].

To consider those possibility and mitigation features into nuclear power plants in Korea in systematic way, the plant-specific thermal-hydraulic response following the LOCA at shutdown modes should be evaluated and the plant-specific mitigating capability necessary to achieve the safe shutdown should be determined. Such a kind of thermal-hydraulic analysis has not been extensively performed, because it was generally believed that the reactor coolant system (RCS) behavior during shutdown LOCA could be bounded conservatively by that during full-power LOCA [3]. Although the differences in decay heat level, initial RCS temperature and pressure, etc. between full-power LOCA and shutdown LOCA may not create the drastic difference in the plant behavior, but may cause a significant reduction of the safety margin, e.g., peak clad temperature (PCT).

And the plant-specific configuration during shutdown operation may change the accident sequence. This aspect can be explained by the recent research on LOCA at modes 5 and 6 [5]. Therefore, it is important to determine if the major thermal-hydraulic phenomena during LOCA could be affected by those differences from the full-power LOCA condition and to determine which effect can be observed if existed. Through this evaluation, the effectiveness of high pressure safety injection (HPSI) can be also identified.

In determining the mitigating capability, it is important to evaluate how much time is available for operator before the initiation of reactor core heatup if HPSI is unavailable following the shutdown LOCA. And the evaluation should be based on the best-estimate calculation. However, little study using best-estimate calculation has been performed in this area, except hot-standby LOCA at VVER type reactor [5]. The purpose of this study is to evaluate thermal-hydraulic response following the LOCA during shutdown condition under the plant-specific features in design and operation, and to evaluate the adequacy of operator action time for mitigate the LOCA in shutdown condition, especially in modes 3 and 4. The YGN Units 3/4 was selected for the present analysis. For this purposes above, the plant design and operation characteristics are investigated and the analysis cases are determined. The thermal-hydraulic behavior following LOCA in shutdown modes is calculated by RELAP5/MOD3.2 [6]. The applicability of the codes to the shutdown LOCA has not been assessed directly, however, the predictability of the code on the major thermal-hydraulic phenomena during the small break LOCA was fully verified for the various thermal-hydraulic tests including LOFT, Semiscale, LSTF, etc. [7]. Based on the code prediction, the difference in thermal-hydraulic behavior from those in LOCA at full power is identified, and the effect of HPSI on plant response is evaluated. And LOCA break spectrum analysis is performed to evaluate an adequacy of operator action time for manual actuation of HPSI.

2. Plant Design and Operation Characteristics

The YGN Units 3/4 were 1000 MWe Combustion Engineering (CE) type PWR, which have been operating since 1995 [8]. The plant has a reactor pressure vessel and two loops. Each loop consists of one hot leg, one steam generator (SG), two crossover legs, two reactor coolant pumps (RCPs), and two cold legs. Each of four cold legs has connections from one safety injection tank (SIT), and from two HPSI pumps and two low pressure safety injection (LPSI) pumps, which provides emergency core cooling (ECC) function. After a planned reactor shutdown, the plant was normally cooled down and depressurized through four operating modes, i.e., hot-standby (mode 3), hot-shutdown (mode 4), cold shutdown (mode 5), and refueling (mode 6). Especially, the hot-standby mode was defined as a reactor state of zero thermal power excluding core decay heat, effective criticality less than 0.99, and cold leg coolant temperature greater than 350°F. Also the hot-standby operation is limited to the interior space of pressure-temperature curves defined in the Limiting Condition for Operation (LCO). The plant conditions at hot-standby mode has no difference in safety system unavailability compared to those at hot-shutdown mode, however, the core decay heat is greater than that at hot-shutdown mode. It indicated that the LOCA at hot-standby mode could lead to more severe condition than LOCA at hot-shutdown mode. Therefore, this study is focused to LOCA at hot-standby mode.

During the hot-standby operation, SG auxiliary feedwater, turbine bypass valves, and atmospheric dump valves are available for core decay heat removal. Charging and letdown operation is also available for inventory control. For ECCS, two independent trains of HPSI and LPSI systems and four SITs are available when the reactor coolant system (RCS) pressure is greater than 12.14 MPa (1762 psia), while one train of HPSI and LPSI system and three SITs are available when RCS pressure is below that value. The operator can block SI actuation in advance or can lower the SI actuation system setpoint pressure by 0.68 MPa (100 psia), when depressurizing the RCS below 12.14 MPa. There are also various systems and components unavailable during hot-standby mode, including some instrumentation and support systems [8].

Based on those design provisions, LOCA at hot-standby mode can lead to a severe condition due to HPSI unavailability, if the conditions used in full-power DBA analysis such as a single failure assumption would be applied consistently. Therefore, it should be confirmed that the available systems could perform their functions against the accident during shutdown operation, as designed. In addition, it should be evaluated which actions are necessary to mitigating capability and how much time will be available for taking the necessary action

3. Thermal-hydraulic Analysis

For the plant-specific evaluation of hot-standby LOCA of YGN Units 3/4, 0.4 % cold leg break LOCA was analyzed. A cold leg break with 0.4 % of the cross-sectional area of cold leg was selected since thermal-hydraulic behavior including two-phase natural circulation could be easily identified [9]. The thermal-hydraulic analysis was conducted in three categories as follows :

1) 0.4 % cold leg break LOCA at full-power: It is used for identifying difference in thermal-hydraulic behavior with the LOCA at hot-standby mode. Initial and boundary conditions were selected to be identical to the final safety analysis report (FSAR) [8]. Loss of off-site power, single failure assumptions, etc, generally assumed in DBA, were applied consistently.
2) 0.4 % cold leg break LOCA at hot-standby mode: It is used to investigate thermal-hydraulic behavior of the plant during shutdown LOCA and to evaluate the effect of HPSI on the plant thermal-hydraulic behavior. Initial and boundary condition were selected as follows:
   - Operating parameters including the RCS pressure, pressurizer level, etc. were determined to be within the plant operating procedure [10].
   - HPSI was either available or unavailable.

Table 1. Initial Conditions of Event of YGN Units 3/4

Parameters	Full-power LOCA(0.4 %) with HPSI	Hot-standby LOCA (0.4 %) with HPSI	Hot-standby LOCAs w/o HPSI	Plant Tech. Spec. & Procedure
Reactor Power, MWth	2871	97.1	97.1	0*
Pressurizer Pressure, MPa	15.51	14.8	12.1	LCO
Hot Leg Temperature, K	601.3	563.4	563.4	
RCS Subcooling, K	16.7	51.3	35.7	>15
Cold Leg Temperature, K	568.9	562.3	562.4	> 449.7
Loop Flow Rate, kg/sec	7673	7720	7826	N/A
Pressurizer Water Level, %	46	18.3	17.2	15~70
SG Level, % (narrow range)	44	43	42	23.4 ~ 90
SG Pressure, MPa	7.58	7.21	7.21	
SG Feedwater Flow Rate, kg/sec	817	36.3	36.3	>36
SG Steam Flow Rate, kg/sec	818	34	34	

Note * : decay power excluded

Single failure assumption was applied consistently.

3) Cold leg break LOCAs at hot-standby mode with a range of break sizes 0.4 % to 4 % : It is used for investigating the plant response with the break spectrum. Initial and boundary conditions were selected as follows:
   - The RCS pressure was selected to be 12.1 MPa (1760 psia), which corresponded to a value just below the HPSI setpoint. ? Since only one train of HPSI was available under this initial condition, it is assumed for HPSI to be either unavailable (by the single failure criterion) or available only by manual actuation.
   - Three SITs were available for all the cases except the one at the broken cold leg.
   - Operator action time for the HPSI actuation was assumed to be 15 minutes.
   - Other conditions were determined consistently with those in the other categories.

Table 1 summarizes the initial condition for the calculations described above. All the parameters obtained from the initialization process were appropriately within the LCO and applicable plant procedure. The difference in loop mass flow rate between two hot-standby cases may due to the difference in RCS pressure and the resultant difference in coolant density.

For the cases defined above, RELAP5/MOD3.2 code [6] was used.

The plant including the primary coolant system and the secondary coolant system was modeled, as shown in Figure 1, with 189 hydrodynamic volumes, 207 hydrodynamic junctions and 212 heat structures. The current modeling includes all the components in reactor vessel, hot leg and cold leg at intact loop and broken loop, two steam generators (SGs), pressurizer, and ECCS.

As shown in the Figure 1, two cold legs in the intact loop were lumped into one cold leg, which was based on that the lumping may have no

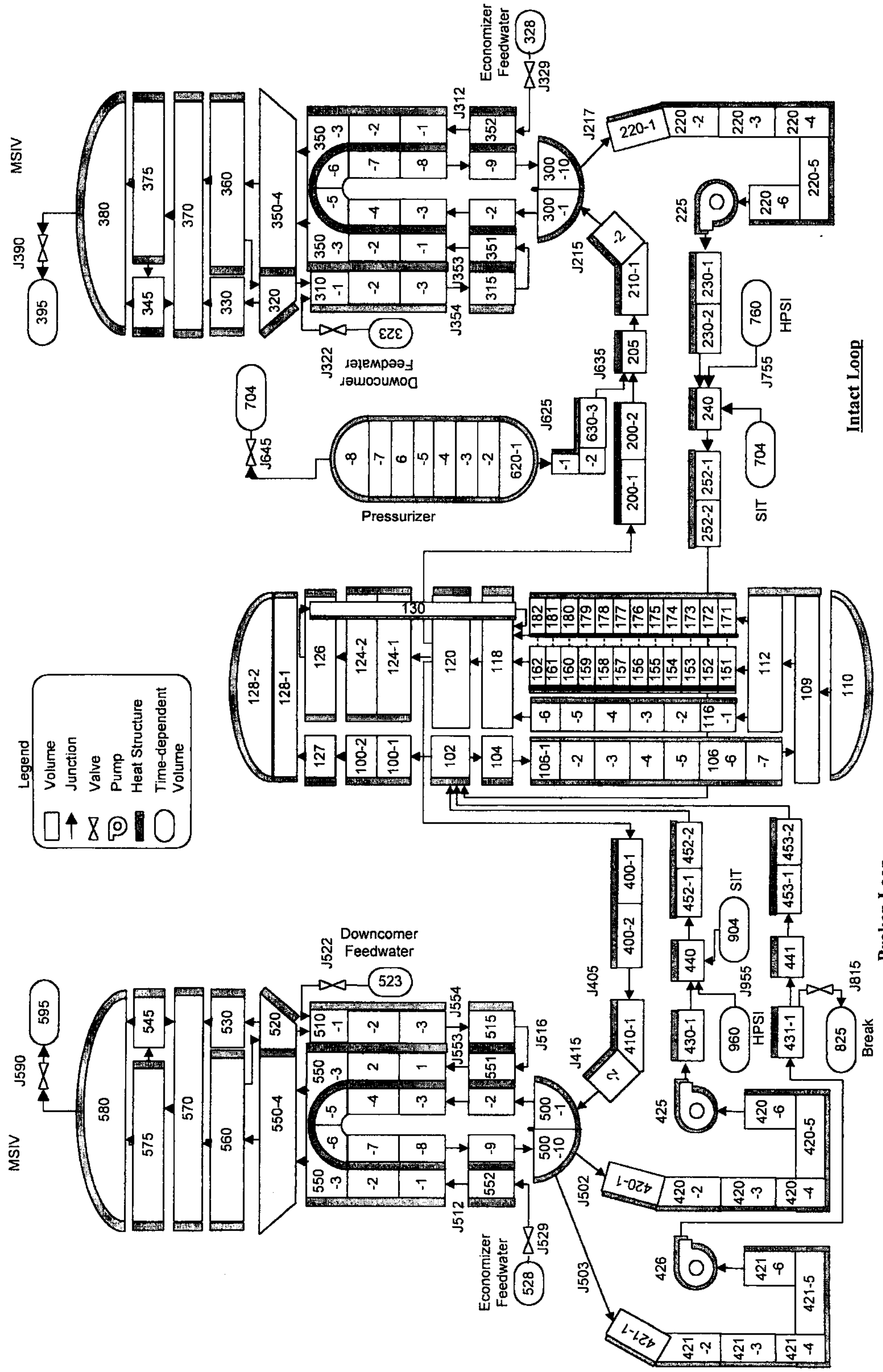

Fig. 1. RELAP5 Nodalization Diagram for Hot-standby LOCA Analysis of YGN Units 3/4

significant impact on the calculation result since the thermal-hydraulic behavior at each cold leg was not believed to be different. In addition, the reactor vessel core was modeled by one average flow channel, one hot channel, and one core bypass channel, which was typical modeling scheme in LOCA calculation to catch out core heatup behavior [9].

4. Results and Discussion

4.1. Blowdown Behavior

Figure 2 shows a comparison of primary system pressures calculated for the three cases: a full-power LOCA with HPSI available; a hot-standby LOCA with HPSI available; and a hot-standby LOCA without HPSI.

In the hot-standby LOCA case with HPSI available, the RCS pressure rapidly dropped after the break initiation, and then, depressurization was slowed down by void formation in the RCS. In 50 seconds, the RCS pressure reached the HPSI setpoint, 12 MPa (1762 psia), at which pressure cold ECCS water was injected into RCS with 60 seconds time delay. At about 600 seconds, the RCS pressure was stabilized at 7.5 MPa, at which pressure the RCS was in a balanced state between the decay heat generated from the reactor core, and HPSI cooling capability and the discharged energy through break flow. At 2100 seconds, one can find a pressure decrease in the hot-standby LOCA with HPSI available, which was induced by break flow increase due to loop seal clearing (LSC), as will be discussed later.

The difference in blowdown behavior between the case of hot-standby and the case with full-power with HPSI available can be summarized as follows :

- A more rapid blowdown was found in the hot-standby LOCA case than that in the full-power LOCA case. This was due to a lower RCS average temperature and resultant smaller subcooled margin in hot-standby LOCA than those in full-power LOCA.
- A re-increase in RCS depressurization rate was found at 400 seconds in the full-power LOCA case while at 550 seconds in the hot-standby LOCA. Such a change in depressurization rate was caused by a formation of peak two-phase natural circulation flow with the increase in the RCS void. The difference was believed to be a complex combination of differences in decay heat level, amount of ECCS water delivered, and void distribution over the loops.
- LSC was delayed in the hot-standby LOCA case, which was also due to less steam generation by decay heat lower than the full-power case.

The effect of HPSI on blowdown behavior was not so significant as shown in Figure 2. However, some minor effects can be evaluated as follows :

- The timing of peak natural circulation was earlier in the case of no HPSI than that in the case with HPSI. This dues to the difference in RCS voiding.
- LSC did not occur until 3000 seconds in the case of no HPSI, which due to the early exhaust of coolant inventory.

4.2. Break Flow Behavior

Figure 3 shows a comparison of break flows for the three cases described above. Each break flow shows a similar behavior as in the blowdown behavior discussed previously. In the case of HPSI available, a sudden increase in break flow at 1650 seconds and a sudden decrease at 2100 seconds were due to LSC phenomena, as discussed previously. As RCS voiding increased, the steam pressure in the reactor vessel upper plenum, hot legs, and U-tubes in SGs increased and thus

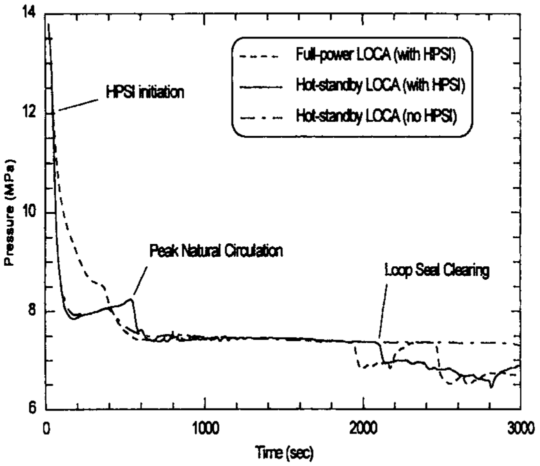

Fig. 2. Comparison of RCS Pressures for Three Cases

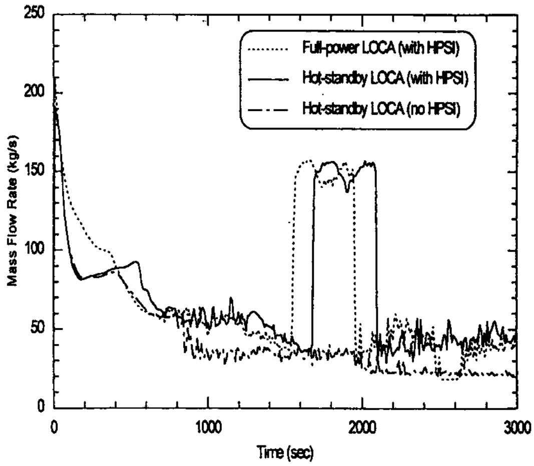

Fig. 3. Comparison of Break Flows for Three Cases

pushed the water in the down-flow side of crossover legs. At the time when the steam pressure was greater than the hydrostatic pressure at the up-flow side of crossover legs, the water in the up-flow side of the crossover legs was expelled into cold leg, i.e., loop seal clearing (LSC). However, the small portion of the water pushed from the crossover legs was delivered into the reactor vessel, and the remaining water was discharged through the break, which contributed a sudden increase in break flow. The calculation result shows the increased break flow was ended at 2100 seconds, which was exactly corresponded to the completion time of LSC.

The difference in break flow behavior between the hot-standby case and the full-power case are as follows:

- More water was discharged through the break in the full-power LOCA case than in the hot-standby LOCA case during subcooled and saturated blowdown phases, which was caused by a pressure difference between the two cases.
- The timing of the break flow increase in the hot-standby case was later than the full-power case, since the hot-standby case had less decay power and less steam generation than the full-power case.

The effect of HPSI on break flow behavior can be identified as follows:

- The break flow in the case without HPSI was, in the overall sense, less than in the case with HPSI during saturated blowdown phase and LSC phase. Total amount of break flow until 3000 seconds was 160,000 kg versus 220,000 kg, while total amount of HPSI flow was 144,000 kg. It indicated that one half of the injected flow was discharged until that time.
- Temporal increase in break flow due to LSC was not found in the case without HPSI until 3000 seconds. It also indicated that the HPSI has contributed to the steam pressure buildup in the hot leg before LSC and refilling hot leg after LSC.

4.3. Inventory Distribution

Figures 4 and 5 show comparisons of liquid fraction at hot and cold legs of the intact loop for

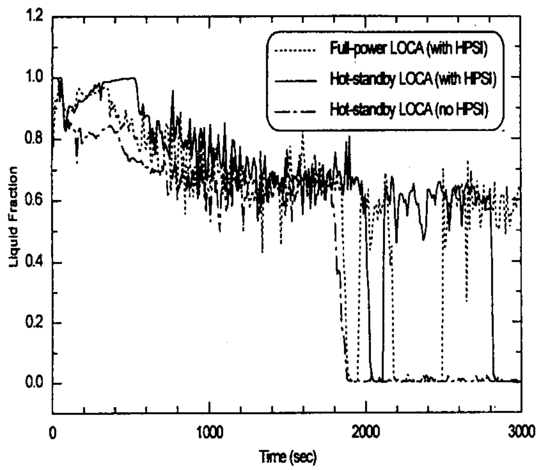

Fig. 4. Comparison of Liquid Fraction in Intact Loop Hot Leg for Three Cases

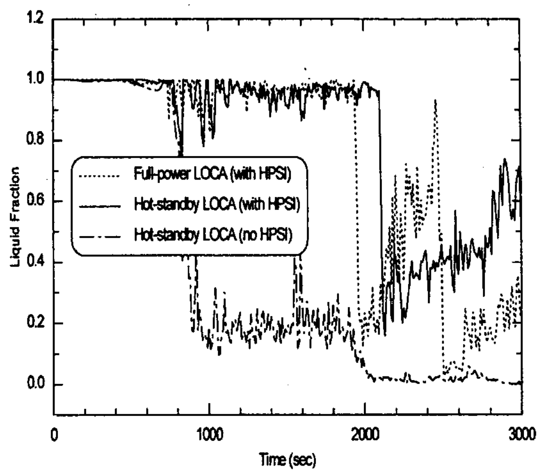

Fig. 5. Comparison of Liquid Fraction in Intact Loop Cold Leg for Three Cases

the three cases above, respectively. After break, the hot leg was first voided and then the cold leg, in the two cases having HPSI. In the hot-standby LOCA case, the hot leg voiding was almost 40 % after 1000 seconds, while the cold leg voiding was less than 10 % during the same time period. It was due to the migration of steam generated from the reactor core into the hot leg.

At about 1950 seconds, the liquid fraction at the hot leg was sharply decreased, and then (about 2100 seconds) re-increased. The liquid fraction in the cold leg was suddenly decreased at 2100 seconds. Those changes in the liquid fraction indicated that steam pushed out the liquid in hot leg from 1950 seconds, and swept out the liquid in the loop seal and the cold leg completely until 2100 seconds, i.e., loop seal clearing. After LSC, the hot leg water level was rapidly recovered up to 60 %, while the cold leg water level was gradually increased by HPSI water.

The level behavior in the broken loop calculated in the present study was almost similar to those at the intact loop.

The difference in the level behavior between the hot-standby case and the full-power case was identified as a delay of loop seal clearing. It is obviously due to less decay heat and resultant less steam pressure in the hot-standby LOCA case than those in the full-power LOCA case. The effect of HPSI was clearly found in both figures. The case with HPSI indicated that hot leg and cold leg had much more water than the case of no HPSI. Especially in cold leg, the liquid was depleted from 800 seconds, before hot leg voiding, which shows a contrasting difference from other two cases.

4.4. Natural Circulation

Figures 6 shows a comparison of mass flow rates at intact loop hot leg for the three cases. At the event initiation, the RCPs were stopped, and the loop flow was rapidly reduced from the 7720 kg/sec to 200 kg/sec, which was a single-phase natural circulation flow established by core decay heat and SG secondary side condition. As the RCS voiding increased, the maximum density gradient through the RCS was established and

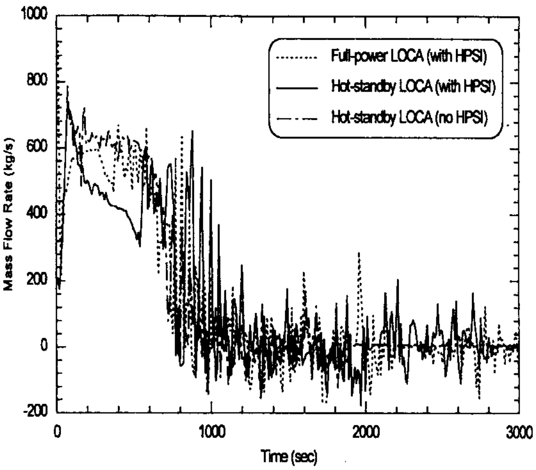

Fig. 6. Comparison of Mass Flow Rates in Intact Loop Cold Leg for Three Cases

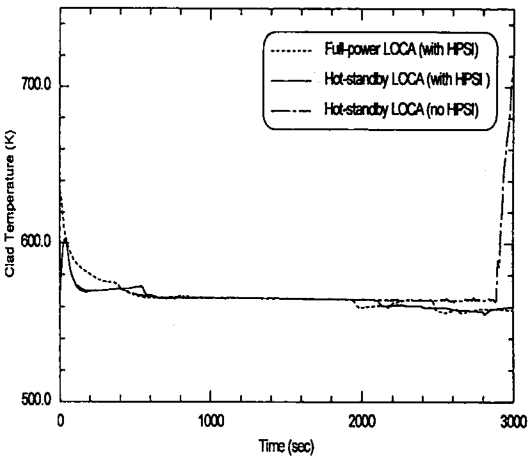

Fig. 7. Comparison of Cladding Temperatures for Three Cases

the peak two-phase natural circulation was attained at 800 kg/sec. Further the RCS voiding re-decreased the loop flow and eventually dropped it to zero level. Each curves in Figure 6 show almost a similar trend with oscillations. The pattern of oscillation was similar to that of hot leg level (as shown in Figure 4), which was believed to be a condensation effect induced by the HPSI.

The second peak in hot-standby LOCA case was quite delayed when compared to the full-power LOCA case. It was also due to the difference in core decay heat and RCS voiding.

The effect of HPSI on natural circulation flow was not clearly identified in this figure. However, the magnitude of oscillation in the case of no HPSI was less than that in the case with HPSI, which due to a reduction of condensation of steam and ECC water. Especially after 2000 seconds, loop flow was nearly zero and had little oscillation in the case of no HPSI. It implied that loop flow pattern was changed, i.e., two-phase natural circulation to reflux condensation due to hot leg emptying.

4.5. Core Thermal Response

Figure 7 shows a comparison of core cladding temperature at the hot spot for the three cases. As shown in the figure, two cases with the HPSI have almost a similar trend and no core heatup until 3000 seconds, while the hot-standby case without HPSI has a rapid heatup starting from 2900 seconds. It indicated that the core level was sufficiently maintained to prevent core heatup.

To summarize, an overall thermal-hydraulic phenomena was observed in both cases of hot-standby LOCA and full-power LOCA, including rapid blowdown, change in depressurization rate due to RCS voiding, two-phase natural circulation, and loop seal clearing. The differences in thermal-hydraulic behavior from full-power LOCA were identified as a faster depressurization rate, a delay in the peak natural circulation timing and LSC timing, which was due to difference in the initial subcooled margin, the decay heat level, and resultant RCS voiding. The effect of HPSI on the plant thermal-hydraulic behavior were evaluated as an enhancement of depressurization by LSC, an

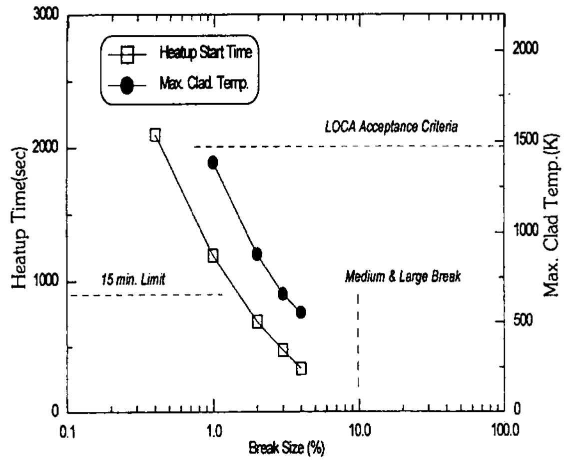

Fig. 8. Results from Break Spectrum Analysis

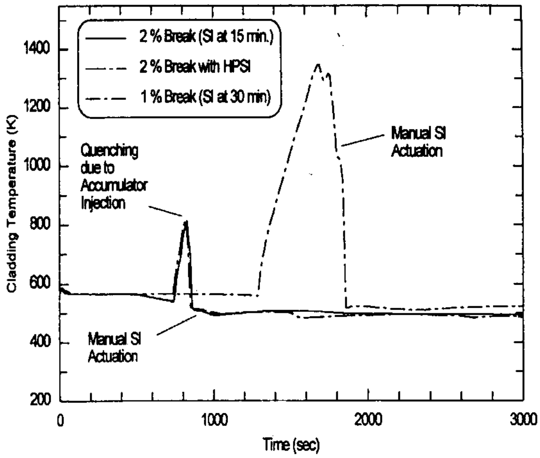

Fig. 9. Comparison of Cladding Temperatures for Breaks of 1% and 2%

extension of two-phase natural circulation by hot leg refilling, and a capability preventing core heatup.

4.6. Break Spectrum Analysis

Figure 8 shows comparisons of the heatup initiation time and the maximum cladding temperature, which were calculated for the hot-standby LOCA without HPSI, for the range of break areas from 0.4 % to 4 % of the cold leg area.

For the 0.4 % break, even if the heatup initiation time was later than 2000 seconds after the transient, however, the PCT was estimated to be greater than the LOCA acceptance criteria [11] of 1447 K (2200°F). For the 4 % break, the heatup was initiated at 300 seconds, the PCT was calculated to be 550 K.

The overall result shows that the earlier heatup was initiated for the larger break size, however, that the higher PCT reached for the smaller break size. This is obviously due to the core cooling by the safety injection tank (SIT) which passively injected cold water into RCS at its setpoint. For the break larger than 2 %, the RCS pressure was rapidly dropped to the SIT setpoint (4.2 MPa) within 1200 seconds. However, for the 1 % break, the break size was not large enough to depressurize the RCS down to SIT setpoint before core heatup. Therefore, the critical break size may be between 1 % and 2 % break, at which size the RCS pressure may not decrease down to the SIT setpoint.

It can be also considered that the calculated PCT may exceed the LOCA acceptance criteria for the break less than the critical break size. However, for the break less than 1 %, the reactor core can be quenched by manual actuation of HPSI, if operator action time for the manual actuation of HPSI was assumed less than 15 minutes. Since, however, there may be uncertainties in the PCT and the heatup starting time calculated by RELAP5/MOD3, the margin of the current result will be further reduced, if the calculational uncertainties are considered.

Figure 9 shows a comparison of cladding thermal response for the following three cases :
2 % break with manual HPSI at 15 minutes; 2 % break with automatic HPSI; and 1 % break with

manual HPSI at 30 minutes. As previously mentioned, the core heatup was arrested by SIT injection for both cases of 2 % break and the calculated PCTs were less than 850 K. For the 1 % break case with 30 minutes for operator action, the calculated PCT was close to 1400 K. Therefore, for the LOCA with critical break size, it may be necessary to take a proper action for depressurizing RCS pressure to the SIT setpoint before the initiation of heatup (between 700 seconds and 1300 seconds).

5. Conclusions

A thermal-hydraulic analysis was conducted on the LOCA during shutdown operation of YGN Units 3/4. Plant-specific characteristics of YGN Units 3/4 in design and operation were reviewed and the analysis cases were determined. Based on RELAP5 calculations, the major thermal-hydraulic behavior during LOCA in hot-standby mode was evaluated, the difference in thermal-hydraulic behavior from those in LOCA at full power was identified, and the effect of HPSI on plant response was evaluated. In addition, an adequacy of operator action time for manual actuation of HPSI was evaluated through the break spectrum analysis. As a result, the following conclusions are made:

1) The plant behavior following the hot-standby LOCA under plant specific design and operational features of YGN Units 3/4 was evaluated for the major thermal-hydraulic phenomena such as blowdown behavior with change in depressurization rate, break flow behavior, inventory distribution with loop seal clearing, natural circulation, and core thermal response.
2) The differences in the thermal-hydraulic behavior from the full-power LOCA includes a faster depressurization, a delay in peak natural circulation timing and loop seal clearing timing, which was due to difference in the initial RCS subcooled margin, the decay heat level, and the resultant RCS voiding.
3) The effect of HPSI on the plant thermal-hydraulic behavior is identified as the enhancement of depressurization by LSC, an extension of two-phase natural circulation by hot leg refilling, and a capability preventing core heatup
4) The break spectrum analysis shows that the critical break size can be between 1 % to 2 %, and that the available operator action time for the SI actuation and the margin in the PCT could be reduced considering uncertainties of the present RELAP5 calculation.

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