Core Liquid Level Depression due to Manometric Effect during PWR Small Break LOCA

Effect of Core Bypass

Masahiro OSAKABE, Taisuke YONOMOTO, Yutaka KUKITA, Yasuo KOIZUMI and Kanji TASAKA

Japan Atomic Energy Research Institute*

Received April 25, 1987

In the previous study, it is reported that the core collapsed liquid level was depressed nearly to the core bottom and the dryout of the core was observed in the early stage of the PWR cold leg small break loss-of-coolant accident (LOCA) experiment. The manometric effect due to the liquid seal formation in the loop seal and the difference of the liquid holdup between the steam generator (SG) upflow-side and downflow-side caused a depression of the core collapsed liquid level. The core liquid level was recovered just after the loop seal was cleared.

The bypass between the core side and the downcomer side affects the core liquid depression. Four 5% cold leg break experiments with the different core bypass location, configuration and size were conducted to clarify the bypass effect. When the bypass was relatively small (less than 3% bypass of the initial core flow before the break), the timing of the loop seal clearing delayed with the bypass. When the bypass was relatively large (9.2% of the core flow), the loop seal clearing took place after the break uncovering and the timing was significantly delayed. In general, the smaller minimum core collapsed liquid level was obtained at the earlier timing of loop seal clearing due to the smaller bypass.

KEYWORDS: small break loss of coolant, PWR type reactors, ROSA-IV, LSTF, manometric effect, coolant loops, seals, bypasses, core liquid depression, dryout, steam generators

I. INTRODUCTION

The Japan Atomic Energy Research Institute has initiated the Rig-of-Safety Assessment Number 4 (ROSA-IV) Program to investigate the thermal-hydraulic behavior of a Westinghouse-type four loop pressurized water reactor (PWR) during small break loss-of-coolant accidents (SBLOCAs) and operational transients. Integral tests of the reference PWR plant behavior using the Large Scale Test Facility (LSTF) are at the heart of this program.(1)(2)

The cold leg break experiments with the break size corresponding to 5% of the scaled (1/48) flow area of the reference PWR's cold leg were conducted by using the LSTF. A recent topic of interest is the early core liquid level depression and dryout due to the difference of the liquid holdup between the steam generator (SG) upflow-side and downflow-side as observed in such experiment as Semiscale experiments(3) and the LSTF experiments(4)(5). The scaling factors of the Semiscale and the LSTF to the reference PWR are 1/1706 and 1/48, respectively.

The SBLOCAs are characterized by the slow primary system depressurization rate and small mass flow rate within the primary loop compared with the design-basis large break LOCA. Because of the slow depressurization rate and the small mass flow rate, the steam and liquid phases in the primary loop tend to separate. Various phase-separation or top-down liquid draining effects dominate both the hydraulic and heat transfer

* Tokai-mura, Ibaraki-ken 319-11.
characteristics of SBLOCAs. The draining rates are different in the core, downcomer, pressurizer, SG U-tubes, SG plena and loop seal. The liquid seal formation in the loop seal and the difference of the liquid holdup in SG (more liquid on the upflow-side than the downflow-side) causes a depression of the core level due to the manometric balance in the primary loop, which is called as the manometric effect.

Shown in Fig. 1 is the illustration of the typical collapsed liquid level distribution in the LSTF primary loop at 120, 140 and 160 s after the break in the previous study. At 120 s after the break, the top-down draining of liquid occurred generally in the primary loop components. At 140 s after the break, the core liquid level reached the minimum level when the steam/water interfaces at the downflow-side of the loop seals (SG side) fell to the loop seals bottom and it was still filled with water. The minimum core collapsed liquid level was below the loop seal bottom as much as the differential pressure between two paths, which are from the core top to the U-tubes top through the hot leg and from the loop seal bottom to the U-tubes top through the SG downflow-side. The differential pressure is mainly due to the difference of the liquid holdup between the upflow-side and the downflow-side of SG. After that, the loop seals were completely cleared as the steam/water mixture moved up the upflow-side of loop seals (pressure vessel side), which is called as the loop seal clearing. At 160 s after the break, the core collapsed liquid level recovered to about 2 m above the bottom of core.

In the steady state operation of the actual PWR, water from the cold leg comes down in the downcomer and enters to the core, however a part of the water bypasses the core. During the core liquid level depression, the pressure at the core side is higher than that at the downcomer side. The bypass between the core side and the downcomer side affects the behavior of the core liquid level depression. In the Semiscale, the amount of core bypass flow had a strong effect on 5% SBLOCA severity as measured by core liquid level depressions. The Semiscale experiments S-LH-1, with 0.9% of the core flow bypassed, and S-LH-2, with 3.0% of the core flow bypassed, showed that the core liquid level depression was greater for the smaller bypass.

The four LSTF 5% cold leg break experiments with the different core bypass were conducted to clarify the bypass effect on the core liquid level depression. Although the bypass in the Semiscale is only between the downcomer to the upper head, the more realistic bypasses such as the hot leg leak line, the downcomer to upper head spray nozzle and the vent valve line are considered in the LSTF. The bypass to measure the primary coolant temperature (resistance thermometer detector (RTD) bypass) are not considered in the LSTF because the recent PWR has quick-response RTD installed directly at the main coolant piping.
II. EXPERIMENTAL FACILITY AND PROCEDURE

The LSTF is a 1/48-scale simulation of a Westinghouse type 4-loop (3,423 MWt) PWR. The elevations of major components are preserved full-scale to represent properly the natural circulation phenomena important to the core cooling during and after SBLOCAs and operational transients. The PWR four loops are represented by two equal-volume loops called A and B loops. Accordingly, the secondary volume and heat transfer area in each SG are scaled at 1/24 of those in the reference PWR. The hot and cold legs are sized to conserve the volume scaling and the ratio of the length to the square root of pipe diameter, i.e. \( L/\sqrt{D} \) of the reference PWR for the simulation of flow regime transition in the primary loop\(^6\).

The four 5% break experiments in the present study were initiated from a pressurizer pressure of 15.5 MPa and hot and cold leg temperatures of 599 and 564 K, respectively. These pressure and temperatures are typical of the reference PWR's rated operating conditions. The maximum core power (10 MW) is 14% of the scaled PWR rated power (3,423/48 = 71.3 MW) and the initial core flow also reduced to be 14% of the scaled PWR core flow to obtain prototypical hot and cold leg temperatures. Also, the initial secondary temperature and pressure were higher than those in the reference PWR to limit the primary-to-secondary heat transfer to 10 MW. The secondary water level in SG was as same as that in the reference PWR.

The transient was initiated by opening the break valve. In these experiments, the break point was located in the B-loop (loop without a pressurizer) cold leg between the coolant pump and the pressure vessel. The break orientation was horizontal in all cases.

Shown in Fig. 2 are the locations of bypass in the LSTF and the flow direction at the LOCA conditions. Three kinds of bypasses, which are the hot leg leak line (between downcomer and hot leg), the downcomer to upper head spray nozzle (between downcomer and upper head), and the vent valve line (between downcomer and upper plenum), mitigate the higher pressure at the core side than that at the downcomer side. Shown in Table 1 are the bypass flow rate (% of the core flow) in the LSTF, Semiscale experiments and the typical PWR. The vent valve line was opened at 60 s after the break in the LSTF experiment SC7.

The transient was initiated by opening the break valve. In these experiments, the break point was located in the B-loop (loop without a pressurizer) cold leg between the coolant pump and the pressure vessel. The break orientation was horizontal in all cases.

Shown in Fig. 2 are the locations of bypass in the LSTF and the flow direction at the LOCA conditions. Three kinds of bypasses, which are the hot leg leak line (between downcomer and hot leg), the downcomer to upper head spray nozzle (between downcomer and upper head), and the vent valve line (between downcomer and upper plenum), mitigate the higher pressure at the core side than that at the downcomer side. Shown in Table 1 are the bypass flow rate (% of the core flow) in the LSTF, Semiscale experiments and the typical PWR. The vent valve line was opened at 60 s after the break in the LSTF experiment SC7.

![Fig. 2 Bypass locations in LSTF](image-url)
Table 1 Bypass flow rate in LSTF and Semiscale experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Bypass flow rate (% of initial core flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hot leg leak</td>
</tr>
<tr>
<td>LSTF SC5</td>
<td>High power</td>
<td>0.2</td>
</tr>
<tr>
<td>LSTF SC7</td>
<td>High power</td>
<td>0</td>
</tr>
<tr>
<td>LSTF SC6</td>
<td>Low power</td>
<td>0.6</td>
</tr>
<tr>
<td>LSTF SC10</td>
<td>Low power</td>
<td>0</td>
</tr>
<tr>
<td>Semiscale S-LH-1</td>
<td>Low power</td>
<td>0</td>
</tr>
<tr>
<td>Semiscale S-LH-2</td>
<td>Low power</td>
<td>0</td>
</tr>
<tr>
<td>Typical PWR</td>
<td>—</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Fig. 3 Core power and secondary pressure transients in high and low core power experiments

In the high power series, the reactor scram occurred at a pressurizer pressure of 13.0 MPa and the turbine throttle valve was closed. Also at the scram, the main feedwater was terminated, the reactor coolant pumps were tripped to initiate coastdown and the turbine bypass system was unavailable due to the assumption of loss-of-offsite power. The auxiliary feedwater was supplied with a 28 s delay after the reactor scram. The safety injection (SI) signal occurred at a pressurizer pressure of 12.3 MPa. The high pressure injection system (HPIS) began emergency coolant injections at 12 s after the SI signal.

In the low power series, the reactor scram occurred at 3.4 s after a pressurizer pressure of 12.6 MPa and the turbine throttle valve was closed. Also at the scram, the main feedwater was terminated, the reactor coolant pumps were tripped to initiate coastdown and the turbine bypass system was unavailable due to the assumption of loss-of-offsite power. The auxiliary feedwater was not supplied. The HPIS began emergency coolant injections at 21.6 s after the reactor scram.

The loss-of-offsite power at the reactor scram and the single-failure of two diesel-generators for the emergency power supply were assumed in the operation of the high and low power series. The delay times of the emergency coolant and auxiliary feedwater injection pumps are for the start-up of diesel-generator.

III. EXPERIMENTAL RESULTS AND DISCUSSION

1. High Power Experiment Series

Shown in Fig. 4 are the transients of primary pressure in the LSTF experiments SC5 and SC7. The total bypass in SC5 and SC7 were 2.3 and 9.2%, respectively, including the vent valve in SC7. The other experimental conditions except the bypass are the same in SC5 and SC7. The timings indicated with scram, HPIS and ACC are the reactor scram, the initiation of the emergency coolant injection with the HPIS and the
accumulator (ACC), respectively. The arrow with L.C. is the timing of the loop seal clearing. In these LSTF experiments, the loop seal clearing in the both loops occurred simultaneously. The secondary pressure were kept approximately at 8 MPa due to the actuation of secondary pressure relief valves. The SG maintained at the secondary pressure of approximately 8 MPa is a heat sink up to approximately 200 s after the break in the both experiments. In the LSTF experiment SC7, the vent valve between downcomer and upper plenum opened at 60 s after the break. In SC5, the steam generated in the core smoothly flowed out from the break point and the depressurization of the primary system was accelerated after the loop seal clearing. In SC7, the loop seal clearing was delayed due to the opening of vent valve and resulted in the moderate depressurization rate of the primary system.

Shown in Fig. 5 are the transients of core collapsed liquid levels in SC5 and SC7. The core collapsed liquid level were depressed to the minimum levels just before the loop seal clearing. In SC7, the loop seal clearing was delayed and resulted in the later core liquid level depression. The slower core liquid depression rate was obtained in SC7 than that in SC5 because the higher pressure at the core side was mitigated with the opening of the vent valve. The detailed mechanism will be explained below in Figs. 10 and 11.

Shown in Fig. 6 are the typical transients of rod surface temperature at the elevation 1.83 m above the core bottom in SC5 and SC7. The elevation 1.83 m is the middle of the core where the power density is the highest. When the core liquid level was depressed, the maximum superheat of approximately 100 K was achieved. Although the core power at the core dryout periods was lower in SC7 than that in SC5, the maximum temperature in SC7 is approximately the same as that in SC5. One of the reasons is the higher heat transfer coefficient due to the quicker core liquid level depression in SC5 compared to SC7.

Shown in Fig. 7 is the transients of heat transfer coefficients at the elevation 1.83 m from the bottom of core in SC5 and SC7. The rod surface
heat flux was calculated with the method(7) to solve the inverse conduction problem by using the measured transient of rod surface temperature and the measured heat generation rate in the rods. The heat transfer coefficient was obtained from the calculated heat flux and the measured superheat of rods surface temperature. The heat transfer coefficient in the core liquid depression periods was higher in SC5 than that in SC7. In the quicker hydraulic depression, a part of water was remained above the dryout point(8). The higher heat transfer coefficient in SC5 are considered to be due to the remaining water.

Shown in Fig. 8 are the collapsed liquid levels at the upflow-side and the downflow-side of the steam generator. After the break, the collapsed liquid levels at the upflow-side and the downflow-side decreased quickly. After about 100 s, the larger liquid holdup was observed at the upflow-side whereas the liquid level rapidly decreased at the downflow-side. The larger liquid holdup at the upflow-side was observed after the two-phase circulation terminated due to the phase separation at the U-tubes top. The difference of the liquid holdup between the upflow-side and the downflow-side makes the core liquid depression with the manometric balance in the primary loops. In the previous study(5), the counter current flow limiting (CCFL) and the condensation of steam was considered to be the two of the reasons for the larger liquid holdup at the upflow-side than that at the downflow-side.

Shown in Fig. 9 is the illustration of the collapsed liquid level distribution just before the loop seal clearing in LSTF SC5 and SC7 experiments. In SC5, the core collapsed liquid level was depressed below the loop seal bottom due to the larger liquid holdup in the upflow-side of SG than that in the downflow-side. In SC7, the core collapsed liquid level was also depressed below the loop seal bottom due to the steam phase at the top of downcomer which comes through the vent valve. The core liquid level was depressed as much as the liquid head at the loop seal upflow-side (pressure vessel side) from the liquid level in the downcomer. In this meaning, the steam phase at the top of downcomer made the lower core level just before the loop seal clearing.

Shown in Fig.10 are the differential pressures between the downcomer and the upper plenum (DP1), and between the loop seal bottom and the pump inlet (DP2). It is necessary that DP1 is larger than DP2 when the loop seal clearing takes place. After the break, DP1 is quickly increasing because the larger steam generation rate at the core side than that at the downcomer side. At the loop seal clearing in SC5, DP1 becomes the maximum value and larger enough than DP2. The DP1 is larger than DP2 as much as the
Fig. 10 Differential pressure between downcomer and core side in LSTF SC5 and SC7 experiments

difference of the liquid holdup between the upflow-side and downflow-side of SG. In SC7 at 60 s after the break, the vent valve opened and tended to mitigate the higher pressure at the core side. When the break uncovery in the cold leg takes place at approximately 300 s after the break, the depressurization of the cold leg was accelerated and DP1 quickly increased. As the liquid in SG had already drained out at the loop seal clearing in SC7, the loop seal clearing took place when DP1 became equal to DP2.

Shown in Fig. 11 are the break mass flow rate and the mixture level in cold leg. The break mass flow rate was measured with the catch tank of break flow and the mixture level in the cold leg was measured with the conduction probe rake. As the low quality two-phase flow continued up to the loop seal clearing in SC5, the break mass flow rate is relatively high. After the loop seal clearing, the mixture level in the cold leg quickly decreased and the high quality two-phase flow was discharged from the break point. For this reason, the primary pressure depressurized quickly after the loop seal clearing in SC5. When the vent valve was opened at 60 s after the break in SC7, the low quality two-phase break flow changed to the high quality two-phase flow and the mixture level in the cold leg decreased. At approximately 300 s after the break, the mixture level in the cold leg became enough below the break orifice hole and the depressurization of the cold leg was accelerated. The depressurization of cold leg increased the differential pressure between the downcomer side and the core side and resulted in the loop seal clearing at 440 s after the break as mentioned above.

Fig. 11 Break mass flow rate and mixture level in cold leg in LSTF SC5 and SC7 experiments

2. Low Power Experiment Series

The low power experiment series LSTF SC6 and SC10 were conducted as the counterpart test to the Semiscale experiments S-LH-1 and S-LH-2\(^{(3)}\). The major experimental conditions such as the setpoints for the emergency procedures, core power curve, the primary pump coastdown curve etc. are the same as the Semiscale experiments.

The total bypass in SC6 and SC10 are 1.5 and 0.4% of the core flow, respectively. The other experimental conditions except for the bypass are the same in SC6 and SC10. The transients of primary pressure were approximately the same among the LSTF SC6, SC10, Semiscale S-LH-1 and S-LH-2.

Shown in Fig. 12 are the transients of the core
collapsed liquid level. In the previous study\(^5\), it is reported that the larger liquid holdup was observed at the larger steam generation rate in the core. As the significant liquid holdup in SG upflow-side were not observed due to the smaller steam generation rate in the core in those low power experiment series, the core liquid level depression was moderate. The timing of loop seal clearing is a little later in SC6 than that in SC10.

![Fig. 12 Core collapsed liquid level in LSTF SC6 and SC10 experiments](image)

Shown in Fig. 13 are the break mass flow rate and the mixture level in the cold leg. The break mass flow rate in SC6 was a little smaller than that in SC10. It is considered that the smaller break mass flow rate in SC6 was due to the larger amount of steam flow through the larger bypass. The mixture level in the cold leg decreased at the loop seal clearing in the both experiments. When the cold leg are almost filled with water up to the loop seal clearing, the previous study\(^5\) showed that the loop seal clearing takes place at approximately 30% residual mass in the primary system. The 30% mass approximately agrees with the calculated mass inventory consisting of water in the lower plenum, downcomer, cold legs and loop seal upflow-side and steam elsewhere. It is possible that the smaller break mass flow in SC6 delays the loop seal clearing when the loop seal clearing takes place at a certain residual mass.

3. Bypass Effect on Timing of Loop Seal Clearing

Shown in Fig. 14 are the relations of the timing of the loop seal clearing and the bypass. When the bypass is relatively small (less than 3% of the core flow), the timing of the loop seal clearing delays with the total bypass. When the bypass is relatively large such as LSTF experiment SC7 (9.2% of the core flow), the loop seal clearing takes place after the break uncovering and the timing is significantly delayed. It is considered that the manometric core liquid level depression and the loop seal clearing do not take place when the bypass is large enough to bypass all the generated steam in the core side to the downcomer side.

![Fig. 14 Relation of bypass and timing of loop seal clearing](image)

Shown in Fig. 15 are the relations of the minimum core collapsed liquid level and the timings of the loop seal clearing. The obtained relation can be classified into the two groups, which are the high and low power experiment series. The temporary core dryout due to the manometric effect were observed in the experiments marked with *. Figure 15 also shows that the smaller minimum core collapsed liquid level was obtained at the earlier timings of loop seal clearing. The core collapsed liquid level was depressed below the loop seal bottom as much as the differential
pressure between the two paths, which are from the core top to the U-tubes top through the hot leg and from the loop seal bottom to the U-tubes top through the SG downflow-side. The differential pressure is smaller at the later timing of the loop seal clearing because of the liquid draining at each component and the decreasing steam generation rate due to the decay core power. For these reasons, the smaller minimum core collapsed liquid level was obtained at the earlier timing of loop seal clearing when the bypass was relatively small (less than 3% of the core flow). When the bypass was relatively large (9.2% of the core flow), the minimum core collapsed liquid level dependend on the residual mass in the pressure vessel.

ACKNOWLEDGMENT

The authors would like to express their appreciation to members of Safety Facility Engineering Services Division, Japan Atomic Energy Research Institute, for their operation of the LSTF.

REFERENCES