Presented are results of an application of a new primary coolant inventory tracking method which was invented for a Westinghouse-type pressurized water reactor, to various kinds of small break loss-of-coolant accident experiments conducted at the Large-Scale Test Facility in Japan Atomic Energy Research Institute.

The uniqueness of this method is that it can track the primary coolant depletion prior to the initiation of inadequate core cooling. The primary coolant inventory is tracked by measuring the water level in the vertical region of each primary loop including the steam generator outlet plenum and by using a simple correlation between the level and coolant inventory. The principal level measuring range corresponds to the primary coolant volumes of approximately 30 to 60% of the initial volume. A limitation of the reactor vessel level indication system is also shown in comparison with this method.

**KEYWORDS:** inventory tracking method, primary loop level meter, coolants, PWR type reactors, loss of coolant, inadequate core cooling, break locations, experimental data, LSTF, full-height simulator, ROSA-IV program

**I. INTRODUCTION**

During 13 yr after the severe loss-of-coolant accident (LOCA) at the Three Mile Island Unit 2 (TMI-2), the focus of the reactor safety research shifted from the generic design-basis accident to the plant-specific operational safety including a reliable accident management methodology. The reliable accident management based on a correct diagnosis of the accident conditions is necessary to take adequate mitigation actions and the old scenario-based plant procedures should be renewed to upgraded procedures.

In early 1980's, additional candidate instruments were studied for detection of the imminence and progression of inadequate core cooling (ICC). Possible parameters were considered as the indication of core exit thermocouples (CETs), the rate of coolant loss or level drop prior to the core uncover, and the extent and duration of the core uncover in addition to the indication of subcooling margin monitors (SMMs). As direct vessel level detection methods in a pressurized water reactor (PWR), the Westinghouse reactor vessel level indication system (RVLIS)(1) and the Combustion Engineering heated junction thermocouples (HJTCs)(2) were developed and installed in the United States PWR.

However, each one instrument has limitations on detecting the ICC conditions as shown in Ref. (3). For example, there is some indication from LOFT (loss-of-fluid test) experiments that CETs can be cooled by water falling back from the steam generator while superheated steam conditions are presented in the core. The SMMs do not provide any information about the possible approach to ICC in a saturated primary coolant condition. The RVLIS-type instrument using differential pressure transducer gives relatively large error when subjected to LOCA conditions. And it
is shown in Ref. (1) that RVLIS can give inaccurate coolant inventory in the vessel in a case of vessel top head break LOCA condition. In addition to these, RVLIS (and also HJTC) detects vessel a water level stuck at the nozzle elevation during a long mass depletion time period after the void accumulation in the upper plenum until the steam generator (SG) primary sides become empty of coolant as shown later. It is, therefore, necessary to study and develop more effective ICC instruments or more effective combined method among them.

This paper describes a new primary coolant inventory tracking method(4) invented for the Westinghouse-type PWR (W-PWR) and its application results to fourteen small break LOCA (SBLOCA) experiments conducted at the Large-Scale Test Facility (LSTF)(5) of the Rig-of-Safety Assessment No. 4 (ROSA-IV) program at the Japan Atomic Energy Research Institute (JAERI). The LSTF simulates a 4-loop W-PWR (3,423 MWt) by full height components and 1/48 volumetrically-scaled fluid volumes (see Fig. 1). These experiments include two TMI-type tests, five break location parameter tests(6) with 0.5% break area which corresponds to 2 in. pipe in the reference PWR, and four 5% break tests.

Fig. 1 Configuration of primary components for W-PWR and LSTF

The main part of this inventory tracking method consists of (1) a primary loop level meter (PLLM)(7)~(9) in each loop, which measures a differential pressure (DP) in the vertical region including the SG outlet plenum (SGOP) and the loopseal downflow-side, and (2) a level data analysis system. Following points of the level data analysis are shown in this paper; (a) a prognosis of the vessel level drop timing ($T_{PV}$) below the nozzle elevation by using the primary loop (PL) level drop timing ($T_{PL}$) at the SGOP top region, (b) a relation between the primary system coolant volume ($V_L$) and an average PL level ($L_L$), and (c) a possible estimation for the primary mass depletion rate ($\dot{M}$) by using the average PL level decreasing rate ($\dot{L}_L$).

II. DESCRIPTION OF PRIMARY LOOP LEVEL METER

1. Description of LSTF

The LSTF was designed to simulate the gravity-dominated phenomena which are important in a SBLOCA or a slow abnormal transient in the PWR, by using full-height and large-sized primary components and sufficient measuring and controlling systems. The LSTF is composed of the 1/48 volumetrically-scaled PWR components including the pressure vessel (PV) with an electrically-heated core and internals, two primary loops with an SG and a primary coolant pump in each loop, pressurizer (PR), break simulation system, emergency-core-cooling system (ECCS) and SG secondary system.

Table 1 compares major design characteristics of the LSTF with those of the reference PWR. The LSTF maximum core power can simulate a 1/48-scaled 14% power of the PWR. The fluid volume distribution in the LSTF primary system simulates that of the PWR except for the SG plena volume, which is twice larger than that of the PWR. The heated core length, the elevations of the primary components including the hot leg top, loopseal (cross-over leg) bottom, SG U-tube top and PR nominal water level are completely the same as those of the PWR. However, the PR length and the primary loop pipe diameter are not simulated because of the design compromising. These design differences between the LSTF and the PWR are discussed in Chap. IV.
Table 1  Major design characteristics of LSTF and Westinghouse-type 4-loop PWR

<table>
<thead>
<tr>
<th></th>
<th>LSTF</th>
<th>PWR</th>
<th>PWR/LSTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (MPa)</td>
<td>16</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>Hot leg temperature (K)</td>
<td>598</td>
<td>598</td>
<td>1</td>
</tr>
<tr>
<td>Core power (MWt)</td>
<td>10</td>
<td>3,423</td>
<td>342</td>
</tr>
<tr>
<td>Core inlet flow rate (kg/s)</td>
<td>48.8</td>
<td>16,700</td>
<td>342</td>
</tr>
<tr>
<td>Number of fuel rods</td>
<td>1,064</td>
<td>50,952</td>
<td>48</td>
</tr>
<tr>
<td>Number of primary loops</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Number of U-tubes per SG</td>
<td>141</td>
<td>3,382</td>
<td>24</td>
</tr>
<tr>
<td>Nominal total fluid volume (m³)</td>
<td>8.01</td>
<td>354</td>
<td>44</td>
</tr>
<tr>
<td>RPV fluid volume (m³)</td>
<td>2.68</td>
<td>132</td>
<td>49</td>
</tr>
<tr>
<td>Total U-tube fluid volume (m³)</td>
<td>1.73</td>
<td>87.1</td>
<td>50</td>
</tr>
<tr>
<td>Total SG plena volume (m³)</td>
<td>1.39</td>
<td>33.4</td>
<td>24</td>
</tr>
<tr>
<td>Heated core length (m)</td>
<td>3.66</td>
<td>3.66</td>
<td>1</td>
</tr>
<tr>
<td>EL₁ of loopseal bottom (m)</td>
<td>1.70</td>
<td>1.70</td>
<td>1</td>
</tr>
<tr>
<td>EL₁ of hot leg top (m)</td>
<td>5.61</td>
<td>5.61</td>
<td>1</td>
</tr>
<tr>
<td>EL₁ of SG plenum top (m)</td>
<td>7.63</td>
<td>7.41</td>
<td>0.97</td>
</tr>
<tr>
<td>EL₁ of U-tube top (m)</td>
<td>18.6</td>
<td>18.6</td>
<td>1</td>
</tr>
<tr>
<td>EL₁ of PR water level (m)</td>
<td>20.1</td>
<td>20.1</td>
<td>1</td>
</tr>
<tr>
<td>Hot leg inner diameter (m)</td>
<td>0.207</td>
<td>0.737</td>
<td>3.56</td>
</tr>
</tbody>
</table>

1 Elevation above heated core bottom

2. Description of PLLM

This primary coolant inventory tracking method is composed of (1) a PLLM in each loop, which measures a collapsed water level between the SGOP top and the loopseal bottom by a DP cell, (2) a level data analysis system, and (3) a temperature compensation system for the DP impulse lines.

The level data analysis system should be capable of processing (a) a loop-averaged level reduction from all the PL levels, (b) each PL level deviation from the averaged level, which is affected by the break location in the primary system, (c) a timing of PL level drop initiation at the SGOP top, (d) a time-averaged level decreasing rate in each loop for estimation of the coolant mass depletion rate, and (e) estimation of the primary coolant volume by using the PL level responses. The application results on the LSTF experiments are shown in the next section.

Figure 2 shows the DP instrumentation for the LSTF PL level measurement. The PL level data in the early stage (old) experiments were obtained by the two DP data including the U-tube downflow-side DP, whereas those in the later (new) stage were reduced by only one DP which covered a wide measuring range. A principal PL level measuring range is focused to a narrow range of 2.23 m above the elevation of vessel nozzle bottom (EL 5.399 m) in the LSTF, whereas that for the W-PWR PLLM is 2.54 m above its vessel nozzle bottom.

This inventory tracking method is used in an abnormal condition under the degraded coolant inventory and the primary pump-stopped condition in which the coolant flow effect is negligibly small. A smaller uncertainty is expected for this PL level measurement than the reactor vessel level measuring instrument (i.e. RVLIS) because there is no significantly frictional components and no heat generation in the PLLM measuring region. In a case of large break LOCA in which the break flow effect cannot be negligible, this inventory tracking method can be used for the system recovery process.

3. PLLM Measuring Range on Level-Volume Relation

Figure 3 shows a relation of the height and the primary fluid volume in addition to the level measuring ranges of the PR level meter and PLLM for both of the LSTF and the W-PWR. The PLLM principal measuring range below the SG U-tubes corresponds to a primary fluid volume range of 27.5~60% of $V_0$ (PR top corresponds to 100% volume of $V_0 = 8.01$ m³) in the LSTF, while that in the PWR corresponds to 27.5~56% of $V_0$ (=354 m³).
Fig. 2 Differential pressure measurement between SG outlet plenum and loop-seal region in LSTF

Fig. 3 Level-volume characteristics and level measuring range for LSTF and W-PWR

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The reason of slightly larger fluid volume in the LSTF PLLM range is the larger SG plena volume than in the PWR. The fluid volume below the core top level is approximately 21% in the PWR and is 20% in the LSTF.

It is shown that the PLLM principal measuring range is close to and above the core region and that approximately 1/3 of the primary coolant volume is covered by this narrow measuring range in both the LSTF and the reference PWR. These are important for the ICC instrumentation on the points of (1) detection of the primary coolant depletion prior to the ICC initiation, and (2) slow level responses which are advantageous for the emergency plant operation to diagnose actual conditions and take suitable actions. On the other hand, the PR level measuring range in the PWR corresponds to primary fluid volume higher than approximately 70% of $V_o$ and can give a limited information only in an early phase of the SBLOCA.

III. PLLM APPLICATION RESULTS ON LSTF SBLOCA EXPERIMENTS

1. Major Experiment Conditions

Shown in Table 2 are 14 experiments conducted at the LSTF with 6 break locations and break sizes ranging 0.5~5% of the 1/48-scaled cold leg area. In these experiments, the high pressure injection (HPI) was assumed to fail until manual actuation by operator after detection of the core heatup initiation. The SB3 test simulated a TMI-type SBLOCA in the reference PWR with 1 pilot-operated relief valve (PORV) stuck open. The PR1 test is a similar one with 3 PORVs stuck open.

<table>
<thead>
<tr>
<th>Break location</th>
<th>0.5(0.45)</th>
<th>1.35</th>
<th>2.5</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurizer</td>
<td>SB3</td>
<td>PR1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV top head</td>
<td>SP2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot leg</td>
<td>SH3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold leg</td>
<td>SCC, SCF</td>
<td>SC1, SC2, SC3</td>
<td>SC8, SCI</td>
<td>LSI</td>
</tr>
<tr>
<td>Loop seal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV bottom</td>
<td>SP1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total number</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

*Corresponds to 1/48-scaled PWR cold leg pipe area.
Runs SB3 and PR1 assumed number of stuck-open PORV of 1 and 3, respectively.

Two hot leg break (HLB) tests with 0.5 and 5% break areas, and 7 cold leg break (CLB) tests with 0.5, 2.5 and 5% break areas were conducted at the similar break elevations. The three 2.5% CLB tests had different break orientations (top, side and bottom of piping). Special break locations of the PV top (upper head), the PV bottom (lower plenum) and the loopseal bottom were selected to study the break location effects on the transient system responses. Three tests of SH3, SCF and SCI were conducted later with the wider (new) DP measuring range between the SGOP top and the loopseal bottom (see Fig. 2).

2. Transients of Primary Water Levels

Prior to ICC Detection in Four 0.5% SBLOCA Experiments

Shown in Fig. 4(a)~(d) are the water level transients in the PR and PV compared with the PLLM DP data in both loops A and B for the following 0.5% SBLOCA tests.

(1) 0.5% CLB Test

Shown in Fig. 4(a) are time responses of the primary water levels in 0.5% CLB test (SCF). As the coolant was depleted through the break, the PR level dropped to the bottom at 225 s after the break and water levels formed in the primary system. Core heatup was observed twice in this test, i.e. after
Fig. 4(a)~(d) Primary water level responses toward ICC condition in four 0.5% SBLOCA experiments

1,806 s in the loopseal clearing period and after 2,023 s in the continuous boil-off period.

It is shown that the PV level was kept almost constant at the PV nozzle elevation from approximately 700 to 1,657 s, i.e. being insensitive to the water depletion in this time period, and that the core heatup started 149 s after this time period. On the other hand, the PL levels started to decrease at 940 and 1,003 s in loops A and B, respectively, and reached the loopseal bottom at 1,880 s. Thus, there was a long time period between the PL level decrease and the first core heatup initiation. The ranges of level-change detection for both the PV and PL level measurements are complementary to each other.

(2) 0.5% HLB Test

Shown in Fig. 4(b) are results of 0.5% HLB test (SH3). Although the PR and PV level responses of this test were similar to those of the CLB test, their timings were later due to the higher break flow quality than in the CLB test. The core heatup initiated at 2,370 s. The effective PV level detection ranges were 360~870 s and from 2,057 s to HPI injection time of 2,782 s.

On the other hand, the PL levels in two loops started to decrease at the similar timings (approximately 930 to 960 s prior to the PV level decrease timing). The level decreasing rates became low after the steam discharge at the break approximately at 1,600 s and the effective measuring range was up to 2,200 s. The level-change ranges for PV and PL levels are complementary to each other as in the CLB test.

(3) 0.5% Vessel Top Break Test

Shown in Fig. 4(c) are results of 0.5% PV top (upper head) break test (SP2). The core heatup initiated at 3,552 s. The PR level responses of this test were similar to the HLB
test shown above. A remarkable finding from this test is an apparently-high PV level which is overscaled for most of the test period. The PV level was detected after 2,718 s (628 s after a water level decrease in the upper plenum). A large pressure difference across the upper core support plate is the reason for this high PV level indication. Thus, a DP-type PV level measurement such as the RVLIS can not be applicable for this type of the accident.

The timing of PL level decrease below the SGOP top was estimated by the U-tube downflow-side DP data as approximately 1,300 and 1,350 s in loops A and B, respectively. The PL levels changed from approximately 1,300 to 2,140 s and they were kept constant after the steam discharge at the PV top break at 2,700 s.

(4) 0.5% Vessel Bottom Break Test

The results of 0.5% PV bottom (lower plenum) break test (SP1) are shown in Fig. 4(d). These are similar as those of the CLB test (SCF). The different features of SP1 test from the SCF test are (1) the continuous primary mass depletion was so long that the whole core was uncovered from 1,498 to 1,636 s despite of the HPI actuation and (2) the loop-seal was cleared by the accumulator (ACC) injection at 2,057 s.

The PL level drop timing below the SGOP top was estimated as 850 and 950 s in loops A and B, respectively. Thus, the range of PL level change was from approximately 850 to 2,057 s and it was complementary to the PV level insensitive range of 700~1,420 s.

3. Prognosis of Vessel Level Decrease below Nozzle Elevation in 14 SBLOCA Experiments

It is commonly shown from the above experiment results (see Figs. 4(a)~(d)) that (1) the timing ($T_{PL}$; ↓) of PL level drop below the SGOP top elevation was significantly earlier than the timing ($T_{PV}$; ↓) of PV level decrease below the vessel nozzle elevation, and (2) the PV level stuck at the vessel nozzle elevation for a long time and started decreasing shortly before the core heatup initiation.

Relations between $T_{PL}$ and $T_{PV}$ for the 14 SBLOCA experiments are shown in Fig. 5, where the $T_{PV}$ at the temporary level decrease due to the loopseal clearing is distinguished by a symbol "T". It is shown that (1) in most of the SBLOCA experiments with a 2.5% or smaller break area, $T_{PV}$ is approximately twice later than $T_{PL}$. The relation of $T_{PV}=2T_{PL}$ is principally due to a result of the level-volume relation shown in Fig. 3. Namely, a primary water volume below the SGOP top is approximately twice larger than that below the vessel nozzle bottom, (2) this is also held in the 5% HLB test (SH1), and (3) in the cases of 5% CLB tests (SC8 and SCI) and loopseal break test (LS1), $T_{PV}$ in the loopseal clearing process tends to approach to the $T_{PL}$ and that in the continuous level decrease, $T_{PV}$ approaches 4 to 7 times of $T_{PL}$.

It is concluded that the timing of PL level drop below the SGOP top elevation is useful for prognosis of the vessel level decrease timing in various cases of SBLOCA despite of the break location effects.

4. Primary Mass Inventory Tracking in 0.5 and 5% SBLOCA Experiments

(1) Estimation of Primary Water Mass and Volume

A transient mass inventory ($M$) in the LSTF primary system is experimentally estimated by accounting the system mass balance as

$$M = M_0 - M_d + M_E,$$  \hspace{1cm} (1)

where $M_0=6,065 \pm 4.5\%$ kg is an initial fluid mass including a steam mass, $M_d$ the discharged mass in the storage tank, and $M_E$ the injected ECC water mass. In a case of TMI-type test (SB3), considerable amount of primary fluid remained in the PR did not contribute to the core cooling. Thus an effective primary mass inventory ($M^*$) is defined for the SB3 test by using a PR fluid mass ($M_{PR}$) as

$$M^* = M - M_{PR}. \hspace{1cm} (2)$$

Then a primary water volume ($V_L$) is estimated by assuming a saturated condition on the whole primary system and using the primary mass inventory $M$ (or $M^*$ for SB3 test) as
where \( V_0 \) is the total primary volume and \( \rho' \) and \( \rho^* \) are water and steam densities at transient saturation condition, respectively.

(2) Water Levels Related to Mass Inventory in TMI-type Test

Shown in Fig. 6 are responses of primary water levels in the TMI-type test (SB3). The PR level was raised highly after initiation of the mass depletion through the stuck-open PORV and it did not drop to bottom for all the test period. The PV level decreased in two inventory ranges of higher than 80% and lower than 45% of \( M_0 \), and it stuck constantly at the vessel nozzle elevation between these ranges. This insensitive vessel level range was approximately 3,000 s for the TMI-type test. The core heatup started later at 36% of \( M_0 \).

On the other hand, the PL level was detected between approximately 74 (at SGOP top) and 48% (at PV nozzle elevation) of \( M_0 \). It is shown that this PL level range almost corresponds to the PV level-stuck range shown above. This PL level range can be shown on the effective primary mass inventory \( (M^*) \) range. An inventory shift of \( (M-M^*) \) was approximately 12% of \( M_0 \). Thus, the principal PL level measuring range corresponds to the effective primary mass inventory range of 36~62% of \( M_0 \) in the SB3 test.

(3) PL Level Responses Related to Primary Water Volume in Five 0.5% SBLOCA Experiments

The PL level responses in the principal measuring range for the five 0.5% SBLOCA experiments, which are already shown in Fig. 4(a)~(d) and Fig. 6, are related to the primary water volume ratio \( (V_L/V_0) \) given by Eq. (3) as shown in Fig. 7. The PL level data in two loops are reduced to a loop-averaged PL level \( (L_L) \), which is an arithmetical mean of them. It is shown that the largely different time transients of the PL levels for the five 0.5% break experiments.
Fig. 6 Responses of primary water levels related to mass inventory in TMI-type test (SB3)

Fig. 7 Loop-averaged PL level related to primary water volume in five 0.5% SBLOCA experiments

converge to a narrow range in this level-inventory relation and that the $V_L/V_0$ is simply given by the $L_L$ (unit; m) for these experiments as,

$$V_L/V_0 = aL_L + b,$$

(4)

where $a = 0.0852 \text{m}^{-1}$ and $b = -0.1101$ are constants. An uncertainty of $V_L/V_0$ is $\pm 6\%$ for the loop-averaged PL level and is $\pm 8\%$ for the PL levels measured in 2 loops. These uncertainties are mainly due to the slightly different mass distribution in the primary system among these experiments, which was caused by the break location effects shown previously.

It is shown in Fig. 7 that the PL levels for the HLB and TMI-type tests agree well. The relation for the PV top break test is slightly shifted from the others due to holding of the excess mass in the upper head.

It is also shown that this relation agrees well with the level-volume relation of the LSTF system (see Fig. 3) within a discrepancy of $\pm 8\%$ of $V_0$. The break location effect on the PL level responses for these 0.5% break experiments was not observed in a higher range of $L_L \geq 6.6 \text{m}$ but in a lower range of $6.6 \text{m} \geq L_L \geq 5.4 \text{m}$ in which the SG plena lower head, PV upper region and pipings of the hot leg, cold leg and top of the loop seal downflow region are included.

Concludingly the transient primary coolant inventory is tracked by the loop-averaged PL level and the simple level-inventory relation (4) for the 0.5% SBLOCA experiments with various break locations, and the slight deviation in each test from this relation is dependent on the specific break conditions. Thus, it is useful for the operator diagnosis on detecting an approaching ICC condition to relate the PL water levels with the transient coolant inventory in any SBOCA conditions.

(4) PL Level Responses in 5% HLB and CLB Tests

Shown in Fig. 8(a) and (b) are the level responses of the PLLM and U-tube downflow region related to the primary water volume ratio for the 5% HLB and CLB tests, respectively. In the HLB test (SH1), the U-tube level data was used to estimate the PL level responses in SGOP above the elevation of EL 6.264 m (see Fig. 2).

In SH1 test, the PL levels started to decrease from slightly higher inventory range than in the 0.5% HLB test because of the
Fig. 8(a),(b) Responses of primary water levels related to primary water volume in 5% HLB test (SH1) and 5% CLB test (SCI)

primary water remained in the U-tubes during this process. However, these PL levels are enveloped within the uncertainty range of ±6%. It is remarkable that the PL level responses of these two HLB tests, which differ approximately as large as five times in their time scales, agree well in the level-inventory relation.

Similarly the PL levels in 5% CLB test slightly deviated from those of the 0.5% CLB test. A deviation of the PL levels in 5% CLB test from the relation (4) is less than 12% of $V_0$. This deviation is due to the loopseal clearing phenomena which occurred earlier (namely at larger coolant inventory) than in the 0.5% CLB test as shown in Fig. 5.

It is also shown that the PL level responses in the principal measuring range for these two 5% break tests did not differ so much on the $V_L/V_0$ scale despite of their different break locations. The break location effect appeared largely in the lower PL measuring range (below EL 5.4 m) which is shown by a dotted line in the figure. Namely, the PL level in 5% HLB test recovered slightly after the steam discharge initiation (at $V_L/V_0=0.3$) but in the 5% CLB test, it did not recover after the loopseal clearing.

The vessel level in the 5% HLB test stuck at the nozzle elevation between a range of $0.58 \geq V_L/V_0 \geq 0.24$, whereas the principal PL level measuring range was approximately $0.55 \geq V_L/V_0 \geq 0.41$. In this case, the ICC did not start until the downcomer water level dropped to the bottom (at approximately $V_L/V_0 \approx 0.1$). On the other hand, the PV level-stuck range was very short in the SCI test. The principal PL measuring range was $0.60 \geq V_L/V_0 \geq 0.46$ and the loopseal clearing was detected in the lower range in the 5% CLB test.

Concludingly, the PL level responses can track the primary coolant inventory with a slightly-shifted level-inventory relation (4) even in the 5% CLB and HLB tests, whereas the break location effect is so significant that the vessel level responses related with the
primary coolant inventory differ largely in these tests.

(5) Possible Estimation of Primary Mass Decreasing Rate

A possible method to estimate a primary mass decreasing rate ($\dot{M}$) is applied to the 0.5% HLB test (SH3) by using a time-averaged level decreasing rate, ($\dot{L}_L$), which was obtained for both two-phase and steam discharge periods (see Fig. 9). $\dot{M}$ was estimated as

$$\dot{M} = \dot{L}_L \cdot \rho \cdot A,$$

where $\rho'$ is the saturated water density and $A$ the equivalent cross-sectional area for the principal PL level measuring range (for example, all the SG plena flow area of $A = 0.82 \text{ m}^2$). It is shown in Fig. 9 that this simple relation could give a similar value and trends of the experimental break flow data both for the two-phase and steam discharge periods. However, both effects of break location and break size on the PL level responses should be clarified quantitatively to determine the equivalent area ($A$) which is useful for general SBLOCA cases.

IV. APPLICATION TO PWR SYSTEM

Most of the PL level responses shown here are expected to appear similarly in the actual PWR plant because the LSTF system is capable of simulating the gravity-dominated fluid behavior in the PWR by the full-height and large-sized components.

Some deviations from the LSTF PLLM characteristics can be observed in the PWR responses as follows. One is a slight deviation of level-volume relation of the PWR primary system from that of the LSTF, principally due to the different pressurizer length, SG plenum volume and primary pipe diameter. However, this deviation can be easily identified for the plant-specific configuration. This affects the relation (4). Second one is a 4-loop effect on the transient system responses. Namely, a ratio of the break flow rate to a coolant mass in one loop of LSTF is 1/2 of the 4-loop PWR. This resulted in moderated break flow effects on the broken loop fluid behaviors in the LSTF. On the contrary, a deviation of the broken-loop PL level from the averaged PL level is expected to give more sensitive information to diagnose the PWR accident conditions than in the LSTF experiments. Moreover, the 4-loop PLLMs are more advantageous on the points of redundancy and reliability.

The PLLM inventory tracking method has a limitation in its measuring range (principal range is only 2.54 m in height). However, the application can be enlarged by combining this PLLM method with the other inventory tracking methods. The PR level indication system combined with the PLLM method is also useful for various types of PWR SBLOCA including the TMI-type transient.

In addition, it should be noted that the PLLM can be used in the PWR normal operation conditions as a kind of coolant flow meter for a water single-phase flow by using its predetermined flow-differential pressure characteristics.

V. CONCLUSIONS

A new coolant inventory tracking method with the PLLM for the Westinghouse-type PWR was applied to the SBLOCA experiments conducted at the full-height PWR simulator. The following are concluded:
(1) The PL level drop timing of $T_{PL}$ at the SGOP top is useful for prognosis of a vessel level drop timing ($T_{PV}$) below the nozzle elevation. The $T_{PV}$ was approximately twice later than $T_{PL}$ in various SBLOCA experiments with break area ratio smaller or equal to 2.5%. In larger break experiments, the loopseal clearing phenomena affected largely this relation.

(2) The PL level responses above the vessel nozzle elevation are useful for tracking the primary coolant inventory prior to the ICC initiation in an inventory range of approximately 30~60% of the total system volume $V_0$. A simple relation (4) was obtained between the coolant volume ratio of $V_L/V_0$ and loop-averaged PL level of $L_L$ from the five 0.5% SBLOCA experiments by assuming a saturated primary system. The uncertainty of $V_L/V_0$ within ±6% for the loop-averaged PL level data is mainly due to the break location effects. In larger break experiments, this relation slightly shifted to higher range due to remaining mass in the U-tubes.

(3) The PLLM method can detect a loop-seal clearing phenomena in the case of cold leg break LOCA by detecting the PL levels in the lower measuring range than the vessel nozzle elevation.

(4) It was possible to estimate a primary mass decreasing rate ($-\dot{M}$) in a case of 0.5% HLB test by assuming an equivalent cross-sectional area (A) in the principal PL level range. However, for general cases of SBLOCA, it is necessary to clarify the break condition effects on the PL levels to determine the equivalent cross-sectional area.

(5) It was clarified that the vessel level stuck at the nozzle elevation for a long time prior to the ICC in all the SBLOCA experiments except for the loopseal clearing process. Therefore, the existing vessel level indication system such as the RVLIS or the HJTCs has a wide insensitive zone with respect to the reactor coolant inventory. The PLLM inventory tracking method, being able to track the inventory changes well ahead of the ICC initiation, can be complementary to these existing level indication systems.

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