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Analysis of the Performance of the Westinghouse Reactor Vessel Level-Indicating System for Tests at Semiscale

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MASTER

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ABSTRACT

The Westinghouse Reactor Vessel Level Indicating System (RVLIS), a differential pressure level measurement system, was tested at SEMISCALE. This report contains the analyses of these tests and the conclusions of these analyses. The tests performed included small break and intermediate break tests. Also, frequency response and natural circulation tests were run and analyzed. The RVLIS always indicated a level less than the two phase froth level. The RVLIS output in early small break tests indicated a level 200 cm greater than actual collapsed liquid level. This discrepancy was caused by structural differences between SEMISCALE and a Westinghouse reactor. Once modifications were made so that SEMISCALE better simulated a Westinghouse PWR, the maximum difference between RVLIS and SEMISCALE instrumentation was 30 cm or 3% which is less than the stated uncertainty of the Westinghouse RVLIS.

I. INTRODUCTION

The accident at Three Mile Island Unit 2, originating on March 28, 1979, has become one of the more intensely studied technological mishaps in history. The Report of the Kemeny Commission presents a careful reconstruction of the events during the week of the accident, from a more human than technical point of view.¹ At least one result of the post-TMI-2 studies was a mandate by the Kemeny Commission to the NRC to "consider the need for additional instrumentation to aid in understanding of plant status."² Through the efforts of the TMI-2 Lessons Learned Task Force, the NRC recommended the installation of additional instrumentation (if required) to "provide unambiguous, easy-to-interpret, indications of inadequate core cooling."³ The Advisory Committee on Reactor Safeguards stated:

"The Committee believes that it would be prudent to consider expeditiously the provision of instrumentation that will provide an unambiguous indication of the level of fluid in the reactor vessel. ...The Committee believes that as a minimum, the level indication should range from the bottom of the hot leg piping to the reactor vessel flange area."⁴

With the publication of NUREG-0737, all operating licensees and applicants for operating licenses were required to provide a description of any additional instrumentation to indicate inadequate core cooling and a time table for its installation.⁵

Westinghouse, a reactor vendor, responded with an Inadequate Core Cooling Instrumentation (ICCI) system which includes the Saturation Margin Monitor (SMM) and Core Exit Thermocouples (CETs) and a differential pressure level measurement system. The latter is referred to as Reactor Vessel Level Indicating System (RVLIS). The differential pressure measurement system has been tested at Westinghouse (Forest Hills Facility) and at the SEMISCALE facility at Idaho National Engineering Laboratory (INEL). This report is an evaluation of the results of these tests at SEMISCALE.

II. WESTINGHOUSE REACTOR VESSEL LEVEL INDICATING SYSTEM (RVLIS)

II.A. Description of Westinghouse Level Indicating System

The RVLIS provides coolant inventory information based on a differential pressure (dp) measurement system and, along with the Saturation Margin Monitor and Core Exit Thermocouples, is a part of the complete ICCI system. A complete description of this system can be found in ref. 6. A brief description of the dp system is included here.

The dp system has two trains of three dp transmitters each. These dp transmitters are connected and used as follows (refer to Figs. 1 and 2):

1. Narrow range - This transmitter is connected between the bottom of the vessel and the top of the vessel to existing penetrations. (On the Upper Head Injection (UHI) plant, the top connection is to the hot legs.) With the vessel empty, the output is 0%, and with the vessel full and pumps off, the indication is 100%. With vessel full and pumps on, the indication is offscale (>100%).
2. Wide range - This transmitter is connected in parallel with the narrow range unit. It indicates 0% with vessel empty and it indicates 33% (15% for a UHI plant) with vessel full and pumps off. With vessel full and pumps on, the indication is 100% on a scale of 0% to 110%. This unit is to be calibrated during installation to indicate reactor vessel differential pressure from which one can infer void fraction with any combination of pumps on and off.
3. Upper range unit - This dp transmitter is connected from the hot legs to the top of the vessel. Westinghouse states that this unit is to be used only during head venting. With vessel empty the indication is 0%, and with vessel full and pumps off, the indication is 100%. With vessel full and pumps on and flow in the instrumented hot leg, the indication is offscale in the 0% direction.

These dp transmitters are located outside the containment wall and are connected to the vessel by armored capillary tubing (Fig. 3). There are two isolators in each impulse line - one close to the vessel connection point and one just inside the containment wall. These isolators have switch contacts to indicate excessive travel of the internal diaphragm (an indication of capillary fluid leakage). These capillary lines are evacuated and then filled with demineralized-deaerated water.

II.B. System Configuration Description

The Westinghouse reactor vessel level indicating system consists of the following components (ref. 7):

ORNL-DWG 82-10181

Fig. 1. Reactor vessel level indicating system for non-UHI plant.

ORNL-DWG 82-10182

Fig. 2. Reactor vessel level indicating system for UHI plant.

ORNL-DWG 82-10183

Fig. 3. Process connection schematic, Train A, non-UHI plant.

1. An ITT Barton Model 351 pressure sensor which has a single bellows and provides isolation from the process fluid. The system at SEMISCALE uses three of these and they displace 122.9 cm^3 ($7 \frac{1}{2} \text{ in.}^3$) of water per 2.54 cm (1 in.) of movement.
2. Sealed capillary tubing, 0.48 cm (3/16 in.) OD $\times$ 0.12 cm (0.049 in.) wall thickness, filled with demineralized deaerated water. Various lengths of this tubing were used as follows: 60 m (200 ft) for the hot leg sensor, 45 m (150 ft) for the seal table sensor, and 75 m (250 ft) for the upper head sensor. These lengths are approximately the same as the lengths installed in a PWR plant.
3. An ITT Barton Model 289A hydraulic isolator (differential pressure indicating switch) which has a dual bellows and provides isolation between the tubing connected to the sensor and that connected to the differential pressure transmitter. The isolators are mounted just outside the containment wall. The hydraulic isolator provides an indication of displacement from -16.39 cm^3 (-1 in.^3) (into the reactor system) to 8.2 cm^3 ($\frac{1}{2} \text{ in.}^3$) (out of the reactor system into the differential pressure transmitter diaphragm). The differential pressure required to drive the isolator to the 16.39 cm^3 (1 in.^3) position is about 25.4 cm (10 in.) of water. The hydraulic isolators at SEMISCALE were set up with a bias into the reactor system of 3.28 cm^3 (0.2 in.^3) to 4.92 cm^3 (0.3 in.^3) at atmospheric pressure. Then, the zero position occurred at 6.895 MPa (1000 psig), and was displaced 3.28 cm^3 (0.2 in.^3) to 4.92 cm^3 (0.3 in.^3) out of the reactor system at 15.51 MPa (2250 psig).
4. An ITT Barton differential pressure transmitter which provides a 4 to 20 mA output that is proportional to the difference between the applied pressures. The total load resistance in the current loop is $1,053 \Omega$ which is composed of a $1000\text{-}\Omega$ load resistor, a $50\text{-}\Omega$, $\pm 0.5\%$ current measuring resistor and $2.7\text{-}\Omega$ wire resistance. With the load resistance established, a 33-V supply voltage would be indicated, but on the advice of ITT Barton, due to more than average resistance in the loop, this voltage was increased to 38 V. The ranges of the three differential pressure transmitters are as follows:

DV*VESSEL	998 cm (393 in.) of water column with 4 mA output 0 cm (0 in.) of water column with 20 mA output
DV*DYNAMIC	-998 cm (-393 in.) of water column with 4 mA output 1524 cm (+600 in.) of water column with 20 mA output
DV*UPHEAD	399 cm (157 in.) of water column with 4 mA output 0 cm (0 in.) of water column with 20 mA output

The static line pressure rating is 20.69 MPa (3000 psig) with a line pressure sensitivity of $\pm 0.20\%$ of maximum span per 6.895-MPa (1000 psig) change.

5. Hewlett-Packard power supply models 6205 B and 6206 B are used. In all three, the voltage is set at 38 V. These power supplies are very stable: 0.01% plus 4 mV. This is equivalent to a ± 7.8 -mV total change at 38 V. The power supply effect on the differential pressure transmitter is small ($\pm 0.025\%$ of span per one V power supply change), and the total change is, therefore, 0.0002% of span.
6. A Taylor Model 1323 J three-pen recorder that has an input impedance greater than 1 M Ω . The zero input is set for 0.2 V and the 100% input is set for 1.0 V, corresponding to an input of 4 mA and 20 mA, respectively. The input signal is derived from the voltage drop across the 50- Ω ($\pm 0.5\%$) current resistor. The slow chart speed is 15.2 cm (6 in.) per h.
7. The same signal that goes to the Taylor recorder goes through a patch panel and into the data acquisition system. The signal passes through a Model 7442 Bay Laboratories signal conditioner and into a Model 5204 Bay Laboratories amplifier. The amplifiers are set up with a gain of 10. The amplifiers have a differential input for isolation, and two outputs. One output is unfiltered and is used for channel monitoring with a digital voltmeter. The other output is filtered with a two-pole Bessel filter with a 50-Hz cutoff frequency. This filtered output is clamped so it will not exceed a magnitude of 10 V. The filtered output passes through a multiplexer into an analog-to-digital converter.
8. The multiplexer and analog-to-digital converter is a Data Technology Corporation Milliverter II. The multiplexer uses solid state switches for multiplexing. The analog-to-digital converter operates with the successive approximation technique using 12 bits (11 bits plus a sign bit) to give 4.9-mV resolution. The specified accuracy is 0.02% of reading ± 2.5 mV. The full-scale value is ± 10 V.
9. The digital output of the analog-to-digital converter enters a Model 2100 A Hewlett-Packard computer and is stored on a Model 531 Daconics disc. The data is retrieved from the disc after a test, decommutated and transferred to digital magnetic tape for further processing. The process can take the form of plots from terminals or be transported to the Computer Science Center in Idaho Falls, Idaho, and entered into the Control Data-Cyber System.

The first four items were furnished by Westinghouse and the remainder by EG&G Idaho, Inc. The signal path is in the same order as listed in the above items.

II.C. Algorithm for Conversion of Differential Pressure Measurement to Liquid Level

The collapsed liquid levels computed in this report were obtained using the following equation (ref. 7):

$$L = \frac{H(\rho_r - \rho_v) - \frac{10^5 * \Delta P_m}{9.80665}}{\rho_l - \rho_v} + D, \quad (1)$$

where

L is the liquid level in cm,

H is the elevation between the upper and lower pressure taps in cm,

ρ_r is the reference leg density in kg/m^3 ,

ρ_v is the steam leg density in kg/m^3 ,

ρ_l is the liquid leg density in kg/m^3 ,

(Densities were computed from the ASME steam tables using pressure and temperature measurements from sensors in the steam and liquid regions of interest.)

ΔP_m is the measured differential pressure in kPa,

D is the distance of the lower pressure tap above (+) or below (-) the reference elevation (cold leg centerline).

Equation (1) is the metric system equivalent to the Westinghouse algorithm, with the term D added to reference the liquid levels to a common elevation (the cold leg centerline).

III. SEMISCALE TEST FACILITY

The SEMISCALE system is a scaled model of the primary coolant system of a commercial four-loop PWR nuclear generating plant. Geometric similarity has been maintained in vessel design, including a 25-foot, full-length electrically heated core. It also has a full-length upper head and upper plenum, thus maintaining the same component elevations as in an upper head injection type PWR vessel. Equipment in the SEMISCALE vessel upper head has been designed with flow areas scaled to the fluid flow paths found in a PWR equipped to inject emergency core coolant in the upper head. The modified volume scaling principle utilized in SEMISCALE is expected to produce vessel liquid level responses to small breaks similar to those of a PWR. The facility is highly instrumented. Vessel instrumentation includes several coolant density and differential pressure measurements capable of determining vessel coolant inventory to a high degree of spatial resolution. The SEMISCALE system, therefore, was one of the better test facilities available for evaluation of differential pressure liquid level measuring devices.

The SEMISCALE Mod-2A system configuration employed for Tests S-UT-3, S-UT-6, S-UT-7, and S-UT-8, is illustrated in Fig. 4. The Mod-2A configuration models a four-loop PWR plant equipped with upper head injection (UHI). For Test S-UT-3, S-UT-6, and S-UT-8 UHI was not used. The test configuration is divided into two loops. One loop represents a single loop of a four-loop PWR plant; this loop contains the break simulator and is called the broken loop. The other loop represents the remaining three loops and is called the intact loop. The system includes a pressure vessel with simulated PWR internals but with an external downcomer, active steam generators in both the intact and broken loops, and pumps in the intact and broken loops.

For SEMISCALE natural circulation tests NC-2, NC-3, and NC-8, only part of the Mod-2A system was used as shown in Fig. 5. The broken loop was removed and the vessel/downcomer penetrations for the broken loop hot and cold legs were capped. Normally, the Mod-2A system includes an intact loop pump; however, this was removed and replaced with a special instrumented spool piece. This spool piece contained an orifice to represent the scaled hydraulic resistance of a pressurized water reactor coolant pump in the locked rotor (stopped) configuration. The vessel was modified from the normal Mod-2A configuration for these tests by removing the vessel upper head. This was necessary to ensure a uniform heatup of the entire system and to avoid condensation on upper head structures. The pressurizer was used only to establish the initial conditions for the tests and was then isolated.

The Westinghouse liquid level indicating system was connected to the SEMISCALE vessel as shown in Fig. 6. This equipment was supplied by Westinghouse.

As shown in the figure, the tested Westinghouse RVLIS consisted of three differential pressure measurements with connections being made at

ORNL-DWG 82-13126

INEL-A-17 408

Fig. 4. SEMISCALE MOD-2A system as configured for S-UT test series.

INEL-A-18 468

Fig. 5. SEMISCALE MOD-2A system configuration for separate effect natural circulation-isometric.

ORNL-DWG 81-17873

Fig. 6. Instrumentation of significance for the Westinghouse RVLIS tests at SEMISCALE.

the vessel top and bottom and on the hot leg pipe. The installation at SEMISCALE is intended to be typical of that in a PWR; thus, the three sensors, the hydraulic isolators, and the differential pressure transmitters were stated by Westinghouse to be functionally the same as standard RVLIS components and were installed and checked out by Westinghouse and SEMISCALE personnel in a manner typical of a PWR installation. The vessel and dynamic differential pressure transmitters are connected to the top of the upper head and the bottom of the lower plenum of the vessel in this configuration. The upper head transmitter is connected to the upper head and the intact loop hot leg. The differential pressure measurements were recorded on a three-pen strip chart recorder and also transmitted to the input to the SEMISCALE data acquisition system.

The resident SEMISCALE instrumentation included several dp cells that spanned selected regions of the facility and numerous densitometers that measured the fluid density at various locations. The dp cells were denoted by $\Delta P1$ through $\Delta P7$ and the densitometers were labeled starting with RV (Fig. 6). The dp and densitometer readings were used to determine collapsed liquid level and two-phase froth level in the vessel, respectively. These level measurements were compared with values determined by the Westinghouse RVLIS. There are many other system measurements that were referred to during this evaluation such as temperatures, flows, pump speeds, and pressures.

At this point, we need to define the terms collapsed liquid level, two phase froth level and coolant level. Collapsed liquid level is the level that would remain after all the bubbles or air were removed from a two-phase mixture. The two-phase froth level is used in this report to mean the level to which two-phase mixture still exists. This level also defines coolant level. The last two levels were identified by a sharp transition in the vessel densitometer output that dropped to a steam-only value. This transition indicated that the froth level had passed this densitometer location.

IV. RVLIS PERFORMANCE AT SEMISCALE TESTS

The RVLIS was installed at SEMISCALE and tests were run in conjunction with several scheduled experiments including small break LOCA and natural circulation tests. RVLIS data were recorded so that system performance could be evaluated for each test. Table 1 identifies the tests for which data were taken. Also, this table identifies, in the reference column, the INEL reports that contain RVLIS data and SEMISCALE data. Further, the computer system at INEL was utilized (via phone line hookup) to run an INEL program called MAGNUM. This program was used to analyze the test data stored on "data bank", an NRC-sponsored data storage facility for data from LOCA experiments throughout the country, including SEMISCALE.

IV.A. Test S-UT-3

The detailed analysis of this test is given in ref. 8, and a summary of this analysis is given below.

An analysis of the performance of the Westinghouse RVLIS showed that the RVLIS gave level readings comparable to the SEMISCALE level instrumentation over similar spans (see Fig. 7). In most cases, the Westinghouse RVLIS produced a level measurement that was approximately equal to the vessel collapsed liquid level (as measured by SEMISCALE dp cells) and that was lower than the two-phase froth level (Fig. 8 is a plot of the Westinghouse RVLIS compared to the froth level that was determined from SEMISCALE densitometers). An exception to this was found when either the Westinghouse or SEMISCALE system spanned the upper core support plate. Differences of up to 150 cm (60 in.) were observed between both these measurements and the SEMISCALE level measurements that did not span the upper core support plate. Figure 9 illustrates this condition and Fig. 10 is an expanded view of the same data. The apparent cause of the differences was a flow restriction in the guide tube structure between the upper head and upper plenum that caused an additional pressure drop. A discussion of these structural differences follows.

According to Westinghouse, the structural differences between SEMISCALE and Westinghouse reactors probably caused the large differences illustrated in Fig. 10. Their schematic of SEMISCALE, illustrated in Fig. 11, shows that the solid guide tubes block flow communication between the upper plenum and the upper head resulting in a two-phase mixture being trapped between the water in the upper plenum and water in the upper head. A typical design of a Westinghouse reactor is illustrated in Fig. 12. These reactors have perforated guide tubes which allows good flow communication between upper plenum and the upper head. According to Westinghouse, the guide tube in SEMISCALE would have to be perforated before the SEMISCALE tests would accurately simulate the behavior of a Westinghouse reactor.

Table 1. SEMISCALE tests with Westinghouse RVLIS

Test No.	Test Type	References
S-UT-3	2 1/2% cold-leg break	7,8*
S-UT-6	5% cold-leg break	9, 10, 11*
S-UT-7	5% cold-leg break with UHI	9, 10, 11*
S-NC-2B	natural circulation, single-, two-phase, and reflux	12*
S-NC-3	natural circulation two-phase	12*
S-NC-8	natural circulation, reflux	*
S-UT-8	repeat of S-UT-6 with modified guide tube	13*
SIB1	100% cold-leg break, survival test for RVLIS	†
SC-WSPT-20	Frequency Response Test of RVLIS	14

*NOTE: Data for analysis was obtained from Data Bank via phone line hookup.

†Informal transmission of data from W. W. Tingle (INEL) to C. N. Miller (ORNL).

Fig. 7. Plot of difference between Westinghouse level measurement and SEMISCALE level measurements in S-UT-3 (for entire vessel, note good agreement).

Fig. 8. Comparison of Westinghouse vessel level measurement with coclant level in SEMISCALE as determined by densitometers for S-UT-3. Note: Vertical transition on this curve indicates passing two-phase level by a densitometer.

Fig. 9. Westinghouse collapsed liquid level (upper head to lower plenum) compared with SEMISCALE collapsed liquid level (-13 cm to lower plenum) for S-UT-3.

NOTE: CURVE 1 - $| (VL\ 13\ M-578) - WVESLV | = \text{DIFFERENCE}$
 CURVE 2 - VL 13 M-578

Fig. 10. Collapsed liquid levels in SEMISCALE as measured by dP 4 (VL13M-578) and WVESLV. (Expanded plot of Fig. 9 with difference between two traces plotted.)

ORNL-DWG 81-17871A ETD

Fig. 11. SEMISCALE simulation of a PWR.

ORNL-DWG 81-17870A ETD

Fig. 12. Westinghouse reactor vessel configuration (PWR).

Evaluation of guide tube effect

The guide tube in the upper plenum at SEMISCALE contains slots only near the bottom. The slots permit flow communication between the upper plenum and upper head. Since the slots are relatively low in the upper plenum, Westinghouse analysis of the S-UT-3 test results and the SEMISCALE configuration showed that a two-phase mixture may be trapped in the guide tube when there is a froth around the lower end of the tube. This trapped mixture adds to the level measured by the Westinghouse RVLIS system, but not the SEMISCALE dp measurement from -13 to -578 since this measurement does not span the upper core support plate. To evaluate this explanation for the difference between these two dp measurements, the following calculations were made.

The top of the first slot is -36 cm below the cold leg and the bottom of the fourth slot is at -91 cm. The guide tube is approximately 437 cm long. The "added" level due to the two-phase mixture in the guide tube can be calculated by

$$\text{"Added" level} = (1 - \alpha) H, \quad (2)$$

where α is the void fraction in the guide tube and H is the guide tube height.

These discrepancies between Westinghouse and SEMISCALE collapsed liquid levels were within the range of the corrections calculated from the values assumed for the height of the mixture in the guide tube. Thus, the guide tube effect appeared to be a plausible explanation for the differences between Westinghouse and SEMISCALE dp measurements.

IV.B. Tests S-UT-6 and S-UT-7

Detailed analysis of S-UT-6 and S-UT-7 is given in ref. 11; a summary of that analysis is contained in this section. The results of the two tests, S-UT-6 and S-UT-7, were similar to those found in test S-UT-3. The Westinghouse RVLIS provided an estimate of the collapsed liquid level which was, in general, less than the actual two-phase froth level as measured by the SEMISCALE densitometers. In S-UT-6, the levels measured by the Westinghouse RVLIS were greater than the levels measured by the SEMISCALE dp instrumentation by up to 200 cm. This is shown in Fig. 13. In S-UT-7, the RVLIS was used only between the hot leg and bottom of the vessel (UHI plant configuration). This eliminated the region of suspected friction losses in the upper support plate area, and the agreement with the SEMISCALE instrumentation was quite good, within 10 cm (see Fig. 14).

As a result of the differences between the vessel collapsed liquid level and Westinghouse instrumentation output, and since Westinghouse claimed that these discrepancies were due to structural differences between SEMISCALE and Westinghouse PWRs, it was decided that new or repeat tests should be run with the internal guide tube

Fig. 13. Westinghouse vessel level measurement compared to SEMISCALE VL13M-578 for S-UT-6.

Fig. 14. Comparison of Westinghouse vessel level measurement to SEMISCALE VL13M-578 for S-UT-7.

modified to improve SEMISCALE's simulation of a Westinghouse PWR. A test, S-UT-8, was added for this purpose; details of this test are contained later in this report.

IV.C. Analysis of SEMISCALE Natural Circulation Tests

A series of natural circulation tests were conducted in which the RVLIS was employed. For these experiments the upper head was removed, thus the upper tap position for the Westinghouse dp cells was 184 cm and the SEMISCALE upper tap elevation was 140 cm. The next three sections of this report contain the analysis of the performance of the RVLIS for tests NC-2B, NC-3, and NC-8.

Analysis of NC-2B

The Westinghouse upper head measurement, WUPHLV, covers a span from +184 cm to +21.6 cm (the hot leg centerline) in the SEMISCALE vessel. The SEMISCALE dp cell that spans approximately the same distance as WUPHLV covers +140 to -13 cm, ΔP_2 . The Westinghouse upper head level measurement is shown in Fig. 15. The measurement indicates that the liquid level drops quickly in the upper plenum which empties by 50 s. Three refills and drains were sensed by WUPHLV at 95 s, 280 s, and 480 s, respectively. In the latter two, the upper plenum was completely filled. The level inferred from a SEMISCALE dp cell, VL140-13M, followed a similar pattern to WUPHLV as depicted in Fig. 16. The upper plenum initially drained in 50 s and refilled and drained three times at 95 s, 280 s, and 480 s. Within limits of the spans covered by the SEMISCALE and Westinghouse measurements, the two agreed within ± 10 cm.

The collapsed level in the entire vessel was monitored by WVESLV and in the core by SEMISCALE dp cell, VL13M-578. The liquid levels inferred in the vessel from these two instruments are plotted as functions of time in Fig. 17 and Fig. 18, respectively. These two plots can only be compared when WVESLV in Fig. 17 reads below -13 cm because the two measurements cover different spans. Both level measurements indicated the same overall trend with an initial decrease and two subsequent refills and drains. The Westinghouse system gave a liquid level value approximately 40-50 cm (15-20 in.) higher than VL13M-578 during most of the test. During the two refills (280 s and 480 s) WVESLV showed a level of nearly +200 cm (vessel full of water) whereas VL13M-578 was not at its upper tap, indicating some voids. Further investigation showed, however, that the densitometer readings were at water-only values throughout the vessel at 280 s and 480 s. It appears that dp 4 (VL13M-578) may have an offset error or slight inaccuracies in its temperature-density corrections for this test, thus causing the level to be -40 cm instead of at its upper tap (-13 cm). This offset could explain why the WVESLV reading is ~40-50 cm higher than VL13-578.

Fig. 15. Westinghouse upper head level measurement (WUPHLV) for NC-2B.

Fig. 16. Upper plenum collapsed liquid level by SEMISCALE
VL140-13M for NC-2B.

Fig. 17. Westinghouse vessel level measurement (WVESLV) for NC-2B.

Fig. 18. SEMISCALE dP level measurement from the upper plenum to the bottom of the vessel (VL13M-578) for NC-2B.

Density measurements from vessel densitometers showed the froth level to be above -11 cm for the first 600 s after rupture except for one brief 20 s period (420-440 s). This dip in froth level is indicated by densitometer readings as low as -313 (RV*23+183) for two periods of ~2-3 s each. The vessel level measured by the Westinghouse RVLIS was lower than the froth (coolant) level for the entire 600 s. At the dip at 420-430 s, WVESLV read ~-370 cm; which was less than the froth level by 60 cm.

From the comparisons with SEMISCALE instrumentation (dp cells and vessel densitometers) the Westinghouse RVLIS measured and trended the vessel coolant level. The RVLIS provided estimates of coolant level which were 40-50 cm (15-20 in.) less than the collapsed liquid level value obtained with the SEMISCALE instrumentation. The collapsed liquid level indication was higher than SEMISCALE measurements but the 40-50 cm is within the uncertainties of either SEMISCALE or Westinghouse measurement systems and may be caused by an offset in the SEMISCALE dp cell.

Analysis of NC-3

The collapsed liquid level in the upper plenum was monitored by Westinghouse dp cell, WUPHLV, and SEMISCALE dp cell, VL140-13M. The span for WUPHLV was +184 to +21.6 cm. The two dp measurements agreed with each other to within ± 10 cm (± 4 in.). The only apparent disagreement was caused by the collapsed level being above or below the dp taps of one of the systems. For example, if the two-phase froth zone spanned the upper tap of a dp transmitter, the output would be the equivalent of the collapsed liquid level of only the froth between the taps. The froth level above the upper tap would not be measured because it is a common mode signal for the dp cell. For example, at 10 s the WUPHLV was reading +175 cm (Fig. 19) and the SEMISCALE dp measurement (Fig. 20) showed a level of +140 cm but this was at its upper tap location, the maximum value for the SEMISCALE dp measurement (+140 to -13 cm).

The collapsed liquid level for the entire vessel was inferred from WVESLV (Fig. 21) and VL140-578 (Fig. 22). WVESLV indicated a vessel full of water for the first 50 s after rupture which agreed with WUPHLV and VL140-13M, Fig. 19 and Fig. 20, respectively. The SEMISCALE dp cell, however, did not indicate a full vessel; but a collapsed level at +110 cm, 30 cm below its upper tap. The reason for this discrepancy is unknown, but it appears to be an offset in the SEMISCALE dp system. At 80 s, the Westinghouse dp measurement showed an approximate level of 30 cm. Both upper head measurement systems indicated a collapsed liquid level of ~20 cm. The SEMISCALE measurement, VL140-578, showed a level of 0 cm; once again a different value than the Westinghouse and the two upper head readings of 20-30 cm. Throughout the remainder of the test, the indicated SEMISCALE level was 30-50 cm lower than Westinghouse value, WVESLV. Both vessel level systems tracked each other very well as functions of time; they indicated peaks and valleys in the vessel level within a few seconds of each other.

Fig. 19. Westinghouse upper head level measurement (WUPHLV) for NC-3.

Fig. 20. SEMISCALE dP level measurement in the upper plenum (VL140-13M) for NC-3.

Fig. 21. Westinghouse vessel level measurement (WVESLV) for NC-3.

Fig. 22. SEMISCALE dP level measurement for the entire vessel (VL140-578) for NC-3.

The in-vessel froth level remained at least as high as -11 cm for the duration of the test (indicated by vessel densitometer RV*UP-11, Fig. 23) and for most of the test the level indicated by WVESLV was above -11 cm. No higher elevation densitometer measurements were taken; thus, further comparisons between vessel froth level by densitometers and the Westinghouse vessel level are not possible.

The Westinghouse RVLIS (both WUPHLV and WVESLV) compared very well with SEMISCALE dp measurements. The two level systems, SEMISCALE and Westinghouse, indicated similar level phenomena such as vessel drains and refills at similar times. Despite an apparent offset in the SEMISCALE vessel level system (VL140-578), the Westinghouse and SEMISCALE collapsed liquid levels were within 50 cm (20 in.) of each other. This is within the expected uncertainty of the Westinghouse RVLIS which is 60 cm (24 in.).

Analysis of NC-8

The collapsed liquid level in the upper plenum was monitored by part of the Westinghouse RVLIS, WUPHLV (taps at +184 and +21.6 cm) and by the SEMISCALE dp cell spanning +140 to -13 cm (VL140-13M). In Fig. 24, both systems showed a rapid draining of the upper plenum; WUPHLV showed a level at its lower tap (+21.6 cm) by 140 s. The SEMISCALE dp measurement indicated a level at its bottom tap (-13 cm) by 900 s but it reached +20 cm at 140 s. Both measurements indicated a vessel full of water at test start, WUPHLV at +184 cm and VL140-13M at 140 cm.

The Westinghouse vessel level, WVESLV, and the SEMISCALE dp cell which spanned the entire vessel, VL140-578, are plotted in Fig. 25. The two measurements tracked each other very well, both in time and in indicated level. The level measurements agreed to within ± 10 cm (4 in.) for 6000 s. Both vessel level indications were similar to the upper plenum dp readings until the water level dropped below the lower tap of the upper plenum dp cells. The range of vessel levels, in this test, was from a full vessel, +184 cm, to -400 cm (equivalent to nearly 3/4 of the core being uncovered).

A possible point that may cause confusion in analyzing the data from this test is illustrated in Fig. 26. The indicated level at 400 s by a SEMISCALE dp cell spanning +140 to -105 was -20 cm. An apparent discrepancy was found when noting that the level given by WVESLV was -100 cm. However, upon further investigation one finds that the dp cell from +140 to -105 was really indicating the collapsed liquid level between its taps, not the vessel collapsed liquid level. A dp cell that does not span the entire vessel will give the correct vessel level only under the special circumstances: (1) when the top of the two-phase froth level is between the two taps, and (2) when there is water-only below its lower tap. For this test, a two-phase mixture existed in almost the entire vessel at 400 s; thus, the above two criteria were

1 RV-UP-11

ORNL-DWG 82-13136

Fig. 23. Fluid density measurement by densitometer RC*UP-11 for NC-3. (Note: The two-phase mixture level never dropped below this densitometer.)

1 WUPHLV

2 VL140-13M

ORNL-DWG 82-13137

Fig. 24. Comparison of Westinghouse upper head level measurement and SEMISCALE VL140-13M for NC-8.

B78

ORNL-DWG 82-13138

1 WVESLV

2 VL140-678

Fig. 25. Comparison of WVESLV and SEMISCALE VL140-578 for NC-8 (both measurements span the entire vessel).

Fig. 26. Collapsed liquid level between 140 cm and -105 cm by SEMISCALE dP measurement (VL140-105) for NC-8.

not met and dp cell 140-105 did not indicate vessel level, only the collapsed liquid level between its taps.

A comparison between two-phase froth level, as determined by vessel densitometer measurements, and WVESLV is shown in Fig. 27. The collapsed liquid level determined by WVESLV followed the two-phase level very closely, ± 20 cm (8 in.). The dashed-line is the minimum two-phase level; the actual froth level may be somewhat higher. The WVESLV level value, collapsed liquid level, is much closer to the froth level elevation for this test than for either S-UT-6 or S-UT-7. In S-UT-6 and S-UT-7, the WVESLV measurement was 70-200 cm below the froth level as compared to 20 cm in NC-8.

Another method for locating the coolant level (two-phase froth level) is by monitoring the temperature excursions of the heater rods. When inadequate cooling occurs in a heated core, there is a sharp increase in heater rod temperature in the regions not cooled. This method can provide a check on the level estimates from the SEMISCALE and Westinghouse dp systems. The lowest temperature excursion noted was at -366 cm; which occurred at 2000 s. At this time, the vessel collapsed level by WVESLV was at -390 cm and vessel densitometers indicated a minimum froth level of -383 cm (Fig. 27). At 4000 s, a sudden increase in heater rod temperatures occurred as low as -313 cm (+183 in the core). The WVESLV was indicating -365 cm while vessel densitometer information yielded a froth level of -383 cm. For both cases, the location of the heater rod temperature excursions followed the trend of two-phase froth level. In addition, the Westinghouse vessel level measurements were lower than the locations of the temperature excursion on the heater rods.

In summary, the Westinghouse RVLIS provided vessel level information that was below the coolant (froth) level. Both the WUPHLV and WVESLV compared very favorably with SEMISCALE dp cells covering similar spans. The agreement between collapsed liquid levels from the Westinghouse and comparable SEMISCALE dp instrumentation was within ± 10 cm (4 in.).

S-NC-2B, S-NC-3 and S-NC-8 Conclusions

For the three natural circulation tests examined in this report, the Westinghouse RVLIS provided unambiguous information as to vessel coolant levels by giving collapsed liquid level estimates that were always lower than the two-phase froth level as determined by vessel densitometers. These RVLIS liquid level estimates compared favorably with SEMISCALE dp instrumentation with similar vessel tap locations.

IV.D. S-UT-8 Test

Test S-UT-8 was a 5% cold leg break LOCA simulation and a repeat of Test S-UT-6 with some exceptions. The exception that most directly concerns the performance of the RVLIS consisted of modifications made

Fig. 27. Comparison of vessel level by WVESLV to minimum two-phase froth level by densitometers for NC-8.

in the fluid flow paths between the upper plenum and upper head. These modifications were made in an attempt to have SEMISCALE more closely simulate the hydraulic resistance and flow paths of a Westinghouse PWR.

The modifications to the SEMISCALE facility that are noted in Fig. 28 included:

1. Support columns were plugged so that all flow must go through the guide tube (note this modification was not implemented properly as will be discussed later)
2. Upper head-downcomer bypass line resistance was increased to limit flow to 2.3% of total coolant flow.
3. UHI tube was removed
4. Guide tube resistance was reduced to 9.3% of bypass line resistance
5. Eight 7.57-mm-diam holes were drilled in the guide tube to permit flow and reduce fluid levels trapped in the guide tube.

Additional instrumentation added to the vessel is shown in Fig. 29. These additions made it possible to compare flow rates and pressure drop ratios from SEMISCALE with those from a Westinghouse PWR.

Unfortunately, Test S-UT-8 did not go as planned. Instrument ports in the support column in the upper head region were inadvertently left open and flow passed through these ports from the upper head to the upper plenum. As a result, the upper regions of the vessel drained very quickly and reduced the period available for comparison of Westinghouse and SEMISCALE collapsed liquid level measurements.

The guide tube effect was to be reduced by the holes added to the guide tube. The previous argument presented by Westinghouse was that fluid in the region surrounding the bottom slots in the guide tube would be drawn into the tube and trapped, thus adding to the Westinghouse vessel level measurement and causing an erroneously high value. The bottom slots range in elevations from -36 to -91 cm. In S-UT-6, the two-phase froth level surrounded the bottom slots until ~500 s (Fig. 30). In S-UT-8 the froth level dropped below the bottom slot (at -91 cm) by ~150 s (Fig. 31). After 150 s, in S-UT-8, only steam surrounds the bottom guide tube slots, thus only steam could have been drawn into the guide tube. Level measurement errors due to steam trapped in the guide tube would be insignificant. Therefore, only data recorded before 150 s should be used in evaluating the guide tube effect and guide tube modifications.

Further inspection showed that the broken and intact loop pumps coasted down to low levels by 85 s. Differential pressure data from rupture until 85 s will include flow-induced and density-head terms. After 85 s the differential pressure will be dominated by the density

* MODIFICATIONS MADE TO BETTER SIMULATE WESTINGHOUSE STD PLANT
UPPER HEAD/UPPER PLENUM FLOW PATHS AND HYDRAULIC RESISTANCES.

Fig. 28. Upper-head upper-plenum schematic drawing showing modifications completed for S-UT-8.

Fig. 29. Required upper-head upper-plenum instrumentation for S-UT-8.

Fig. 30. Collapsed liquid level in the upper plenum by SEMISCALE VL13M-105 for S-UT-5.

Fig. 31. Vessel collapsed liquid level between -13 and -105 cm by SEMISCALE dP VL13M-105 for S-UT-8.

term. Thus, the available region for data comparisons to evaluate the guide tube effect is approximately 85 to 150 s. A plot of the RVLIS output compared to SEMISCALE output is in Fig. 32 and Fig. 33 is an expansion of this plot.

A comparison of collapsed liquid level data from WVESLV and SEMISCALE dp cell covering +135 to -578 cm is shown in Table 2 and Fig. 34. The two instruments agree to within ± 30 cm for the range of interest. A comparison for similar instruments in S-UT-6 yielded differences of up to 200 cm. At least for the short time interval for which "valid" data is available, the agreement between Westinghouse and SEMISCALE dp measurement of collapsed liquid level was much improved over the S-UT-6 test.

The ratio of pressure drops between the downcomer and upper head and upper head and upper plenum were on the order of 8-20 to 1. According to Westinghouse the ratio should be ~ 15 to 1 for a Westinghouse PWR. Thus, we conclude that hydraulic resistances were matched reasonably well in S-UT-8.

Summarizing, the results of S-UT-8 tend to validate Westinghouse's assertions that the guide tube at SEMISCALE caused the discrepancies in collapsed liquid levels for the S-UT-3 and S-UT-6 tests. Marked improvement was noted in comparing liquid levels in S-UT-8 and hydraulic resistances seemed to match values in a Westinghouse PWR.

IV.E. SIB1 Test

This test was a 100% cold leg break and the purpose of recording the Westinghouse RVLIS indication was to assess its survivability and to determine if it trended coolant level upon vessel recovery. Figure 35 is a plot of the Westinghouse narrow range dp transmitter output. Also, plotted on this figure are passage points of the two-phase froth level indicated by SEMISCALE densitometers. The RVLIS output always indicated a lower level than the two phase froth level. The Westinghouse RVLIS did survive and it did trend the coolant level during the partial recovery.

IV.F. SC-WSPT-20 (Frequency Response) Test

Because the dp transmitters in the RVLIS system are located remotely at different distances from the measurement points (45, 60, and 75 m for the three tap points), there was a concern that the system time response would be too slow. Time response can be calculated from system frequency response. The frequency response of the RVLIS system as installed in SEMISCALE and to be installed in reactor vessels was calculated using the equation from ref. 15:

Fig. 32. Comparison of WESLV [curve (1)] and SEMISCALE VL135-578 [curve (2)] for S-UT-8.

Fig. 33. Comparison of WVESLV [curve (1)] and VL135-578 [curve (2)], expanded version of Fig. 28 between 100-300 s, for S-UT-8.

Table 2. Comparison of collapsed liquid level data
for WVESLV and SEMISCALE VL135-578 for S-UT-8

Time after rupture (s)	WVESLV (cm)	VL135-578 (cm)
85	-90	-110
90	-115	-150
100	-150	-180
110	-170	-180
120	-150	-150
130	-155	-170
140	-210	-220
150	-250	-250
160	-280	-310

Fig. 34. Difference in measured level between WJESLV and VL135-578 as a function of time after rupture for S-UT-8.

Fig. 35. Plot of Westinghouse narrow range unit (WVESLV) vs time for test S-IB-1 (+ and † indicate passage of two phase froth level).

$$f = 4.22 \left(\frac{D^2}{L} \frac{dp}{dv} \right)^{1/2}, \quad (3)$$

where

f = the three db frequency response in Hz,
 4.22 = constant in the equation to take care of unit conversion,
 D = inside diameter of the tube in inches,
 L = length of the tube in feet.
 dp/dv = compliance of the dp transmitter ITT Barton Model 752,

supplied by vendor to be $\frac{1000 \text{ in. of water}}{0.2 \text{ in.}^3}$,

units are in $\frac{1 \text{ lb/in.}^2}{\text{in.}^3}$.

Calculating the frequency response of the Westinghouse level monitoring system from equation (3) yields:

$$f = 4.22 \left(\frac{8.1 \times 10^{-3} \cdot 36.13}{400 \cdot .02} \right)^{1/2} = 0.81 \text{ Hz}.$$

Rise time is $2.2(1/f) = 2.2 \cdot 1/0.81 = 2.73 \text{ s}$. This time constant compares favorably with the SEMISCALE test data that are shown below.

Further, the SC-WSPT-20 test was conducted to measure the frequency response. The test was run by pressurizing the system (SEMISCALE) to about 7.1 mPa and inducing a step change down to (common mode pressure change) about 2.1 mPa. The pressure step was created by opening and closing a drain valve. Data were taken and the time response was measured. Figure 36 illustrated the narrow range dp response to this change which was begun at 2 s. It can be seen that the output is at its final value after about 10 s or an 8 s response time. The normal response of system to within 10% of final value is 2.3 time constants and with the calculated time constant of 2.73 s, the calculated response is 6.28 s. The test data in Fig. 36 indicated that the output is within 10% of the final value at about 8.5 s which is a difference of 6.5 s. The comparison of calculated to measured time response showed excellent agreement:

2.3 time constant response of the RVLIS = 6.28 s calculated and
 $\frac{6.55 \text{ s measured.}}{0.22 \text{ s difference}}$

The other data curves from this test showed comparable results, and were not included since they contained no new information. There is good correlation between estimated and measured time response, and this time response is within the required time response of a vessel level measurement system.

Fig. 36. Time response curve for WVESLV (test S-IB-1).

V. CONCLUSIONS

The conclusions of our analysis are:

1. In S-UT-3 and S-UT-6 tests the RVLIS indicated a lower level than the two-phase froth level. [The froth level can only be identified when it passes a particular (from two phase to steam, or vice versa) densitometer at some point in time. Therefore, the froth level is known only at some discrete point in time (when a density transition occurs at a particular densitometer). Because the froth level is known at only discrete points in time, maximum or minimum errors or differences are hard to define.] During these tests the RVLIS indicated a higher level than the vessel collapsed liquid level by as much as 200 cm. This was caused by differences in the upper internals of SEMISCALE; see below for conclusions reached as a result of the repeat test, S-UT-8.
2. In the S-UT-7 test the RVLIS showed good correlation with the vessel collapsed liquid level and the RVLIS indication was well below the froth level. This was a UHI test.
3. In the S-NC-2B, S-NC-3 and S-NC-8 tests there was good correlation between the collapsed liquid level and the RVLIS output. The RVLIS indications were less than the two-phase coolant level.
4. In the S-UT-8 (a repeat of S-UT-6) test the RVLIS showed good correlation to the collapsed liquid level; the difference was less than 3% throughout the test. This test confirmed the Westinghouse guide tube effect discussed in Sect. IV.A.
5. The time response test confirmed Westinghouse calculations of the RVLIS response time (one time constant of 2.7 s).
6. The Westinghouse RVLIS survived an intermediate break S-IB-1 (a 100% cold leg break) and was able to provide trending information after the blowdown.

For the reader's information, Westinghouse has also analyzed the test data that was evaluated in this report and their analyses are documented in refs. 16 and 17.

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