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QUICK LOOK REPORT FOR SEMISCALE MOD-2A TEST S-NC-4

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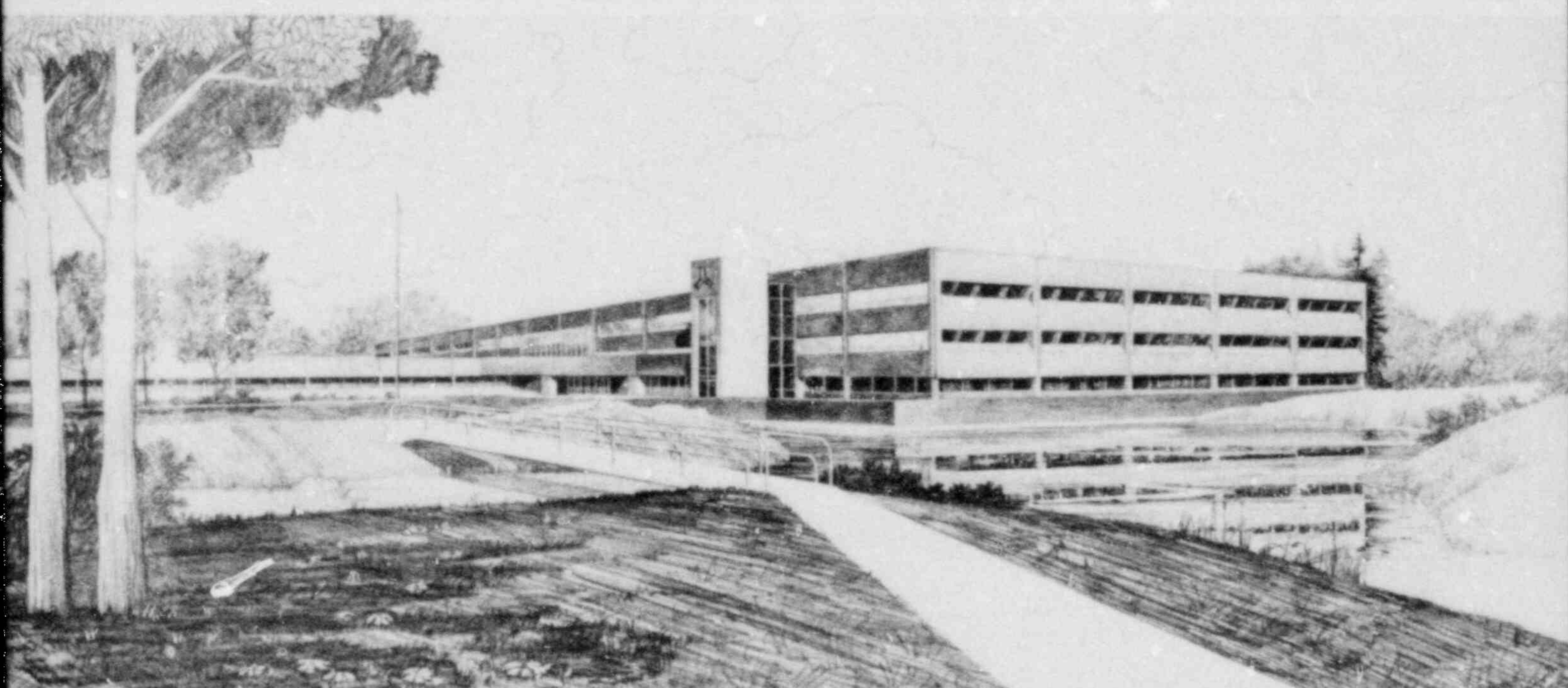

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QUICK LOOK REPORT FOR

SEMISCALE NATURAL CIRCULATION TEST S-NC-4

by

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August 1981

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ABSTRACT

Results are presented from a preliminary analysis of Semiscale Mod-2A Test S-NC-4. Test S-NC-4 was a reflux natural circulation test designed to examine the influence of steam generator secondary side liquid inventory on the natural circulation flow rate and primary system conditions. The reflux mode of natural circulation is a two-phase state characterized by vapor continuous conditions at the inlet of the steam generator (primary) with counter-current liquid flow returning to the vessel. Data were taken for core powers of both 30 and 60 kW. The primary system fluid inventory varied between 48 and 70% and the secondary side collapsed liquid level was varied from 100% to 25% full. Parameters examined include the reflux vs carryover flow split, system fluid distribution, and system temperatures.

SUMMARY

This report presents results from a preliminary analysis of data from Semiscale Mod-2A natural circulation Test S-NC-4. This test was a reflux natural circulation test involving one loop of the Mod-2A system. The broken loop and vessel upper head were removed and replaced with end caps, leaving the intact loop, vessel with downcomer and intact loop steam generator. The intact loop pump was removed to eliminate leakage and replaced with a spool piece designed to have a hydraulic resistance scaled for a locked rotor condition. Test S-NC-4 involved examining the effect on the reflux natural circulation flow rate due to varied steam generator secondary fluid inventory. The steam generator secondary side pressure was maintained constant at 6.0 MPa. The collapsed liquid level in the secondary was changed in discrete increments from 100% (tubes fully covered) to 24%. The experiment was performed at both 30 kW and 60 kW core power (1-1/2% and 3% of full power) and the primary system pressure was allowed to vary. A total of 12 measurements of reflux mass flow and carryover mass flow were obtained. Liquid was measured with the use of special spool piece at the inlet to the steam generator which diverted the refluxing liquid film into a standpipe where it was collected and measured. Liquid carryover was measured by closing a valve in the cold leg thus causing liquid to collect in the pump suction piping where it was measured. External heaters were used on the vessel and loop piping to offset heat losses from the system.

Analysis of flow measurements showed that the reflux-to-carryover flow split was approximately 1:1 for both the 30 kW and 60 kW core power cases. A small decrease in this ratio occurred at secondary side inventory below 50% for a measurment made at 30 kW core power. Reducing the secondary side inventory had little impact on primary pressure for secondary inventories above 50%. At a secondary inventory of 24% the primary pressure rose from 6.2 MPa to 6.9 MPa. For a core power of 30 kW conditions in the primary provided adequate core cooling for all steady-state points. It was found, however, that the core dried-out for secondary inventories of 50% or lower at 60 kW. Reasons for this dryout will be determined in further posttest analysis.

The use of lenses and video equipment in the steam generator inlet plenum and inlet and outlet piping was a valuable tool for verifying the occurence of reflux conditions. Observation of fallback (reflux) in the inlet pantleg also helped qualitatively verify the efficiency of the reflux meter. The meter was indicated to be approximately 100% efficient at 30 kW core power and slightly less at 60 kW.

Calculations performed with the RELAP5/MOD1 code failed to predict the occurence of a steady-state reflux cooling mode. From examination of calculated results it was determined that the vapor velocities in the steam generator tubes exceeded the flooding velocity, thus, preventing liquid fallback. In general there was good agreement between predicted and measured primary pressures and hot leg temperatures.

1. INTRODUCTION

Testing performed in the Semiscale Mod-2A system is part of the water reactor safety research effort directed toward assessing and improving the analytical capability of computer codes which are used to predict the behavior of pressurized water reactors (PWR's) during postulated accident scenarios. For this purpose, the Mod-2A system was designed as a small-scale model of the primary system of a four-loop PWR nuclear generating plant. The system incorporates the major components of a PWR including steam generators, vessel, pumps, pressurizer, and loop piping. One loop (intact loop) is scaled to simulate the three intact loops in a PWR, while the other (broken loop) simulates the single loop in which a break is postulated to occur in a PWR. Geometric similarity has been maintained between a PWR and Mod-2A, most notably in the design of a 25 rod, full-length (3.66 m) electrically heated core, full-length upper head and upper plenum, component layout, and relative elevations of various components. The scaling philosophy followed in the design of the Mod-2A system (modified volume scaling) preserves most of the important first order effects thought important for small break loss-of-coolant transients. Most notably the 1:1 elevation scaling of the Semiscale system is an important scaling criterion for preserving the factors influencing natural circulation behavior.

The tests currently being conducted in Mod-2A are part of the Natural Circulation (NC) test series.[1] The primary objective of the Natural Circulation test series is to provide data that can be used to develop and assess computer models used to predict small break loss-of-coolant accidents or operational transients involving loss of primary pumping. To achieve this objective both steady-state, separate effects type experiments, and transient small break experiments are being performed.

This report presents a preliminary analysis of data from Semiscale Test S-NC-4. This test was a steady-state, separate effects type experiment involving a single loop of the Mod-2A system (the intact loop). The Mod-2A system was modified by replacing the vessel upper head with a simple end cap and replacing the intact loop pump with a spool piece. The broken loop was decoupled from the system. These modifications allowed for a more tightly controlled experiment with ultra-small natural circulation flow rates. Test S-NC-4 was a two-phase natural circulation test designed to provide data on the effect of steam generator secondary conditions on natural circulation flow while in a reflux mode. To establish the reflux natural circulation conditions, primary fluid was drained from the vessel lower plenum. Fluid was also drained from the steam generator secondary in discrete steps to examine the effect of different collapsed liquid levels on the natural circulation flow rate.

A preliminary analysis of Test S-NC-4 data is presented in the following sections . Section 2 describes the system hardware and test conduct. Section 3 presents results from test data analysis. Section 4 discusses results from the pretest prediction. Section 5 presents conclusions drawn from the preliminary analysis.

2. SYSTEM CONFIGURATION AND TEST CONDUCT

2.1 System Configuration

For Semiscale natural circulation Test S-NC-4 only part of the Mod-2A system was used as shown in Figure 1. The test configuration consisted of the vessel with electrically heated core and external downcomer, intact loop tube-and-shell steam generator, and loop piping. 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 was orificed to represent the scaled hydraulic resistance of a pressurized water reactor primary 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 vessel core consists of a 5 x 5 array of internally heated electric rods, 23 of which were powered. The rods are geometrically similar to nuclear rods with a heated length of 3.66 m and an outside diameter of 1.072 cm. All 23 heated rods were powered equally.

The intact loop steam generator is a tube and shell design. Primary fluid flows through vertical, inverted, U-shaped tubes and secondary coolant passes through the shell side. The steam generator has 2 short, 2 medium, and 2 long tubes representative of the range of bend elevations in a PWR steam generator. A horizonal cross section of the intact loop steam generator tubes is shown in Figure 2. The "off-center" arrangement of tubes was required to provide better volume scaling of the secondary. The same tube stock (2.22 cm OD x 0.124 cm wall) and tube spacing (3.175 cm triangular pitch) used for PWR U-tubes were used in the steam generator. Since the heat transfer area was specified based on the ratio of PWR to Semiscale core power, the number of tubes was thereby fixed by the specified tube diameter and lengths. Fillers are installed in the shell side to provide a more properly scaled secondary fluid volume. Elevations

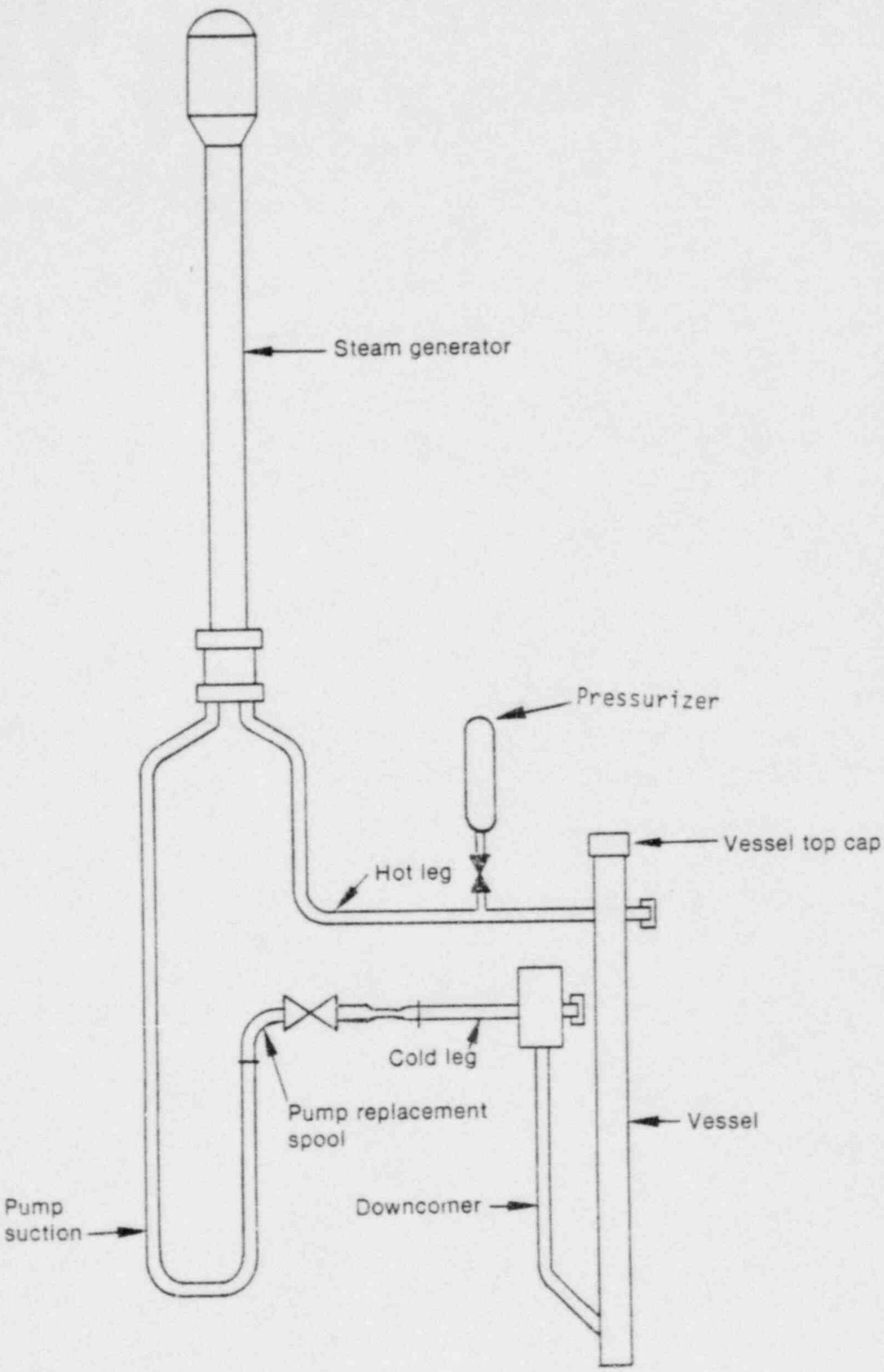

Figure 1. System configuration for Test S-NC-4.

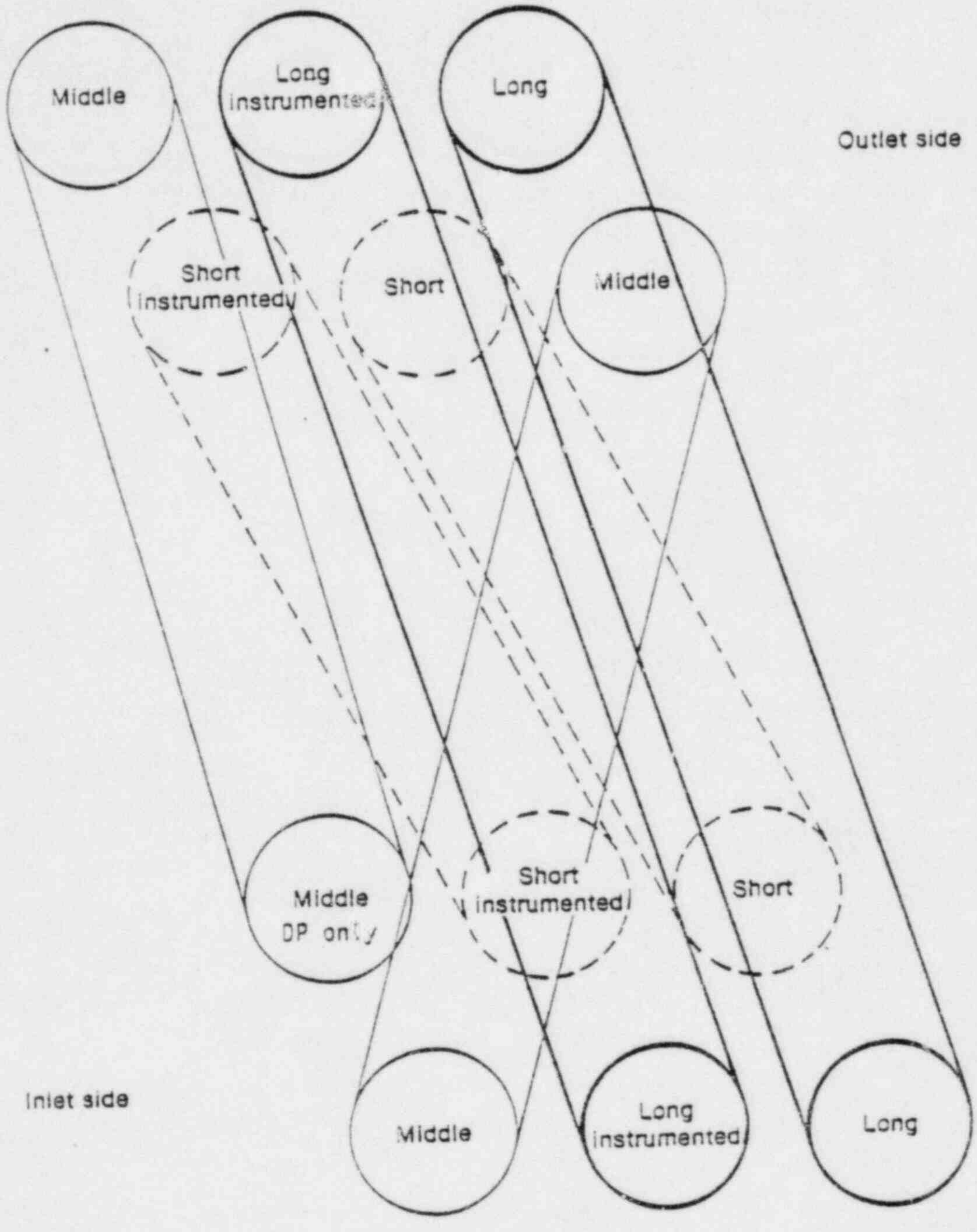

Figure 2. Horizontal cross section of the intact loop steam generator tubes.

of steam generator nozzles, plenums, and tubes are similar to those of a PWR; however, the steam dome is shorter than a PWR steam dome. The steam drying equipment is of a simpler and less efficient design, but is of little importance at the low steaming rates used in the NC test series.

Basically, the system was configured as a heat source (represented by the vessel core) and a heat sink (represented by the steam generator secondary) all connected by loop piping. External heaters were installed on the vessel and loop piping to offset environmental heat loss. The heaters are controlled by four independent, variable power supplies. The distribution of heater power used for Test S-NC-4 is as follows:

Component	Heater Power (kW)
o Intact loop hot leg, including steam generator inlet and outlet piping	4.8
o Pump suction	4.0 to 5.0
o Cold leg	1.0 to 2.0
o Vessel with downcomer	15.5 to 18.5

Results from the Heat Loss Characterization test series[2] were used as a guide in applying external heater power to compensate for heat loss.

2.2 Special Natural Circulation Measurement Techniques for Test S-NC-4

The Natural Circulation test series presents unique ranges of hydraulic conditions relative to the majority of previous Semiscale testing. Low flow rates are the main measurement challenge. For this purpose, turbine meters and drag screens throughout the system have been ranged as low as reasonably possible. The steam generator primary and secondary sides have been extensively instrumented with thermocouples. At several axial locations throughout the steam generators, pairs of primary and secondary fluid thermocouples along with primary tube wall metal thermocouples have been attached to the primary tubes as shown in Figure 3. One long tube and one short tube is extensively instrumented; the middle tubes have no thermocouples installed. Tubes that are instrumented are identified on Figure 2.

Depiction of a typical fluid thermocouple installation is shown in Figure 4. The thermocouple leads are attached to the OD of the primary tubes for a short distance before being routed to a separate support tube. Primary fluid thermocouples penetrate the tube wall with the penetrations sealed with a gold braze. The tube wall thermocouples are attached to the OD of the tube wall as shown in Figure 5. A groove in the tube wall accepts a special thermocouple which has had the tip flattened for a distance of 0.017 cm. The thermocouple is secured in the groove with a braze. In addition to tube thermocouples the steam dome has several fluid thermocouples and the downcomer has fluid thermocouples at several axial positions. Other steam generator instrumentation includes tube (primary side) differential pressure ports allowing measurements of collapsed liquid level in the tubes. The sense lines connecting the measurement location and the differential pressure cell penetrate the side of the steam generator shell at several elevations. Differential pressure ports are located on the long tube that has the thermocouples as well as a middle tube and a short tube. Differential pressure ports are located at the following elevations (in cm) above the tube sheet: 92, 462, 838 in the short tube, and 905 cm in the middle tube, and 970 cm in the long tube. The differential pressure ports are all located on the upflow side of the tubes. Ports are also located in the inlet and outlet plena.

Special optical probes that penetrate the pressure boundary, with video camera capability are used for directly viewing the fluid in the steam generator inlet and outlet piping and the inlet and outlet plena of the steam generator. Visual monitoring is extremely valuable in observing the transition between the various modes of natural circulation and for qualitatively verifying the collection efficiency of the reflux meter.

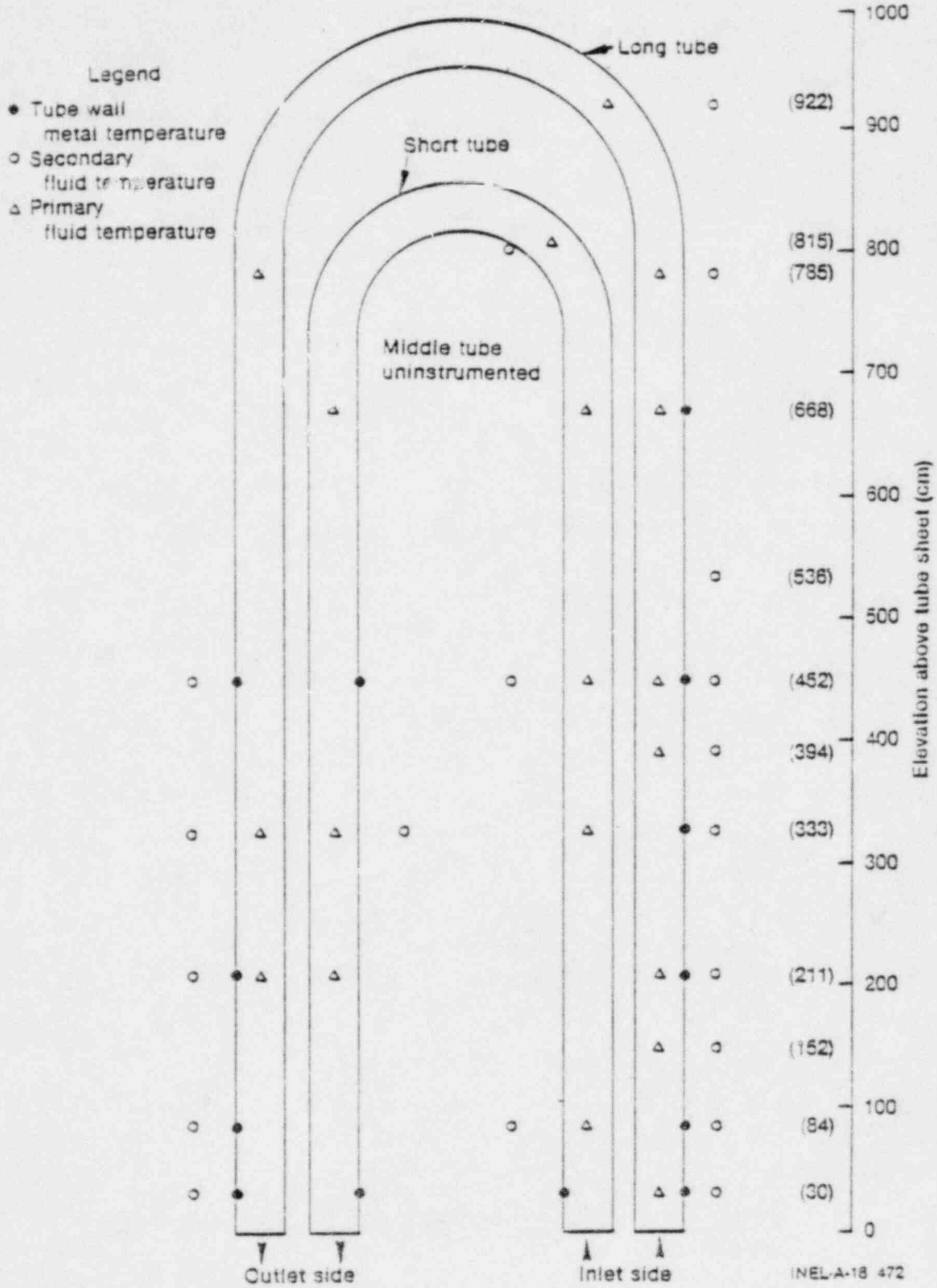

Figure 3. Intact loop steam generator thermocouple locations.

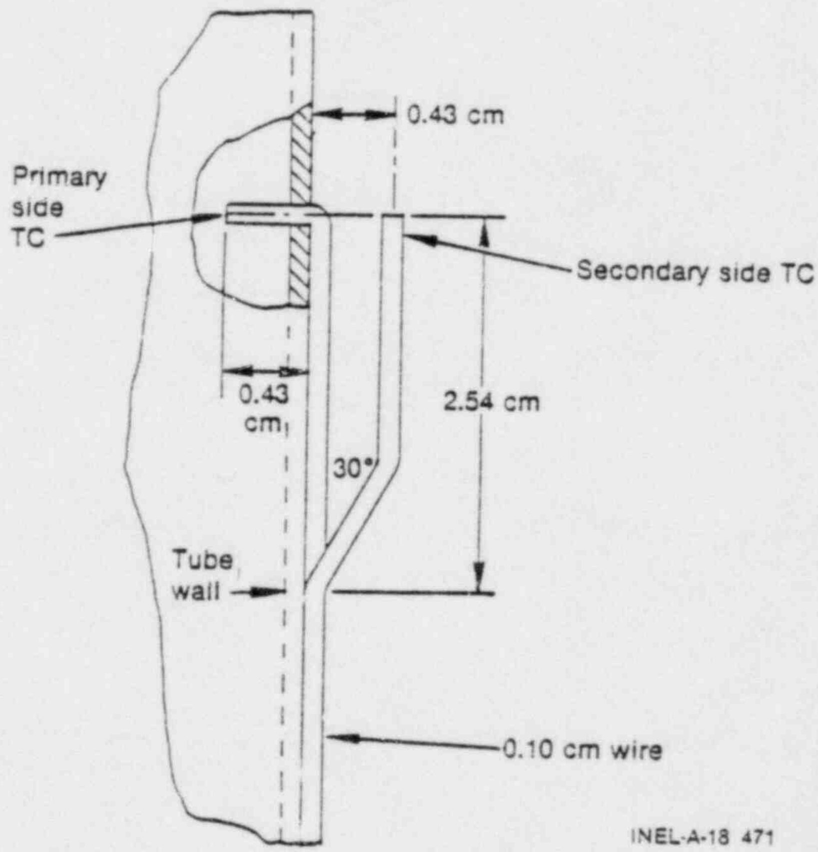

Figure 4. Intact loop steam generator fluid thermocouple installation.

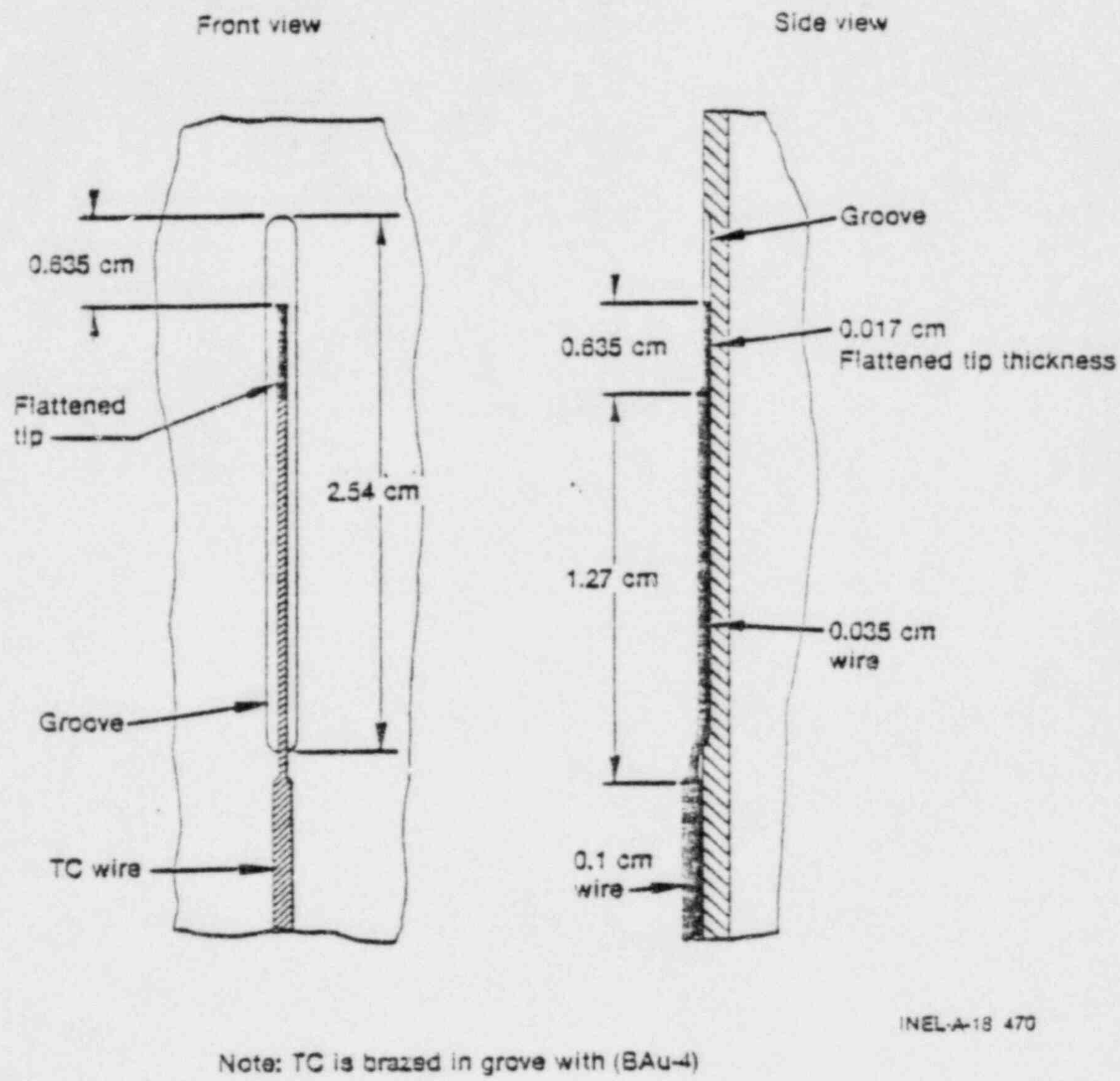

Figure 5. Intact loop steam generator metal thermocouple orientation.

Figure 6 shows a simplified diagram of the "reflux meter" used during S-NC-4 to obtain direct mesurments of refluxed mass flowrates. The device consists of a T spool piece with a weld bead around the inside circumference, and a standpipe for collecting and measuring the liquid. In operation the standpipe, and connecting tubing, are kept full of liquid until a steady-state condition is established in the primary with reflux flow visually observed in the piping below the T. The reflux meter is then drained to a desired level and allowed to refill. Testing was done in an air-water system to determine the efficiency of the T arrangement for stripping off reflux flow.[3] A collection efficiency vs flowrate curve was determined which showed that the efficiency approached 100% for the flowrates encountered in the actual NC tests.

A special drain tank and valve was installed near the vessel lower plenum to collect drained water for controlling the system mass inventory. Fluid from the Mod-2A vessel lower plenum was condensed with special cooling coils and then allowed to enter the drain tank. Tank mass inventory was measured using a static differential pressure measurement.

2.3 Test Conduct

Prior to the initiation of the test, the Semiscale system was filled with demineralized water and vented to ensure a liquid-full system. Instrumentation was calibrated and zeroed as necessary. The system was heated using core power as a heat source and the steam generator secondary as a heat sink. System leak checks were performed periodically during warmup.[a] Natural circulation flow was used to thermally condition the system to the specified steady-state conditions. The reflux mode of natural circulation was established by draining discrete amounts of fluid out of the lower plenum until reflux flow was visually observed in the steam generator primary inlet piping. The pressurizer was valved out of

a. Measured system leakage was negligible at 6.0 MPa and less than 0.001 kg/s at 8.6 MPa.

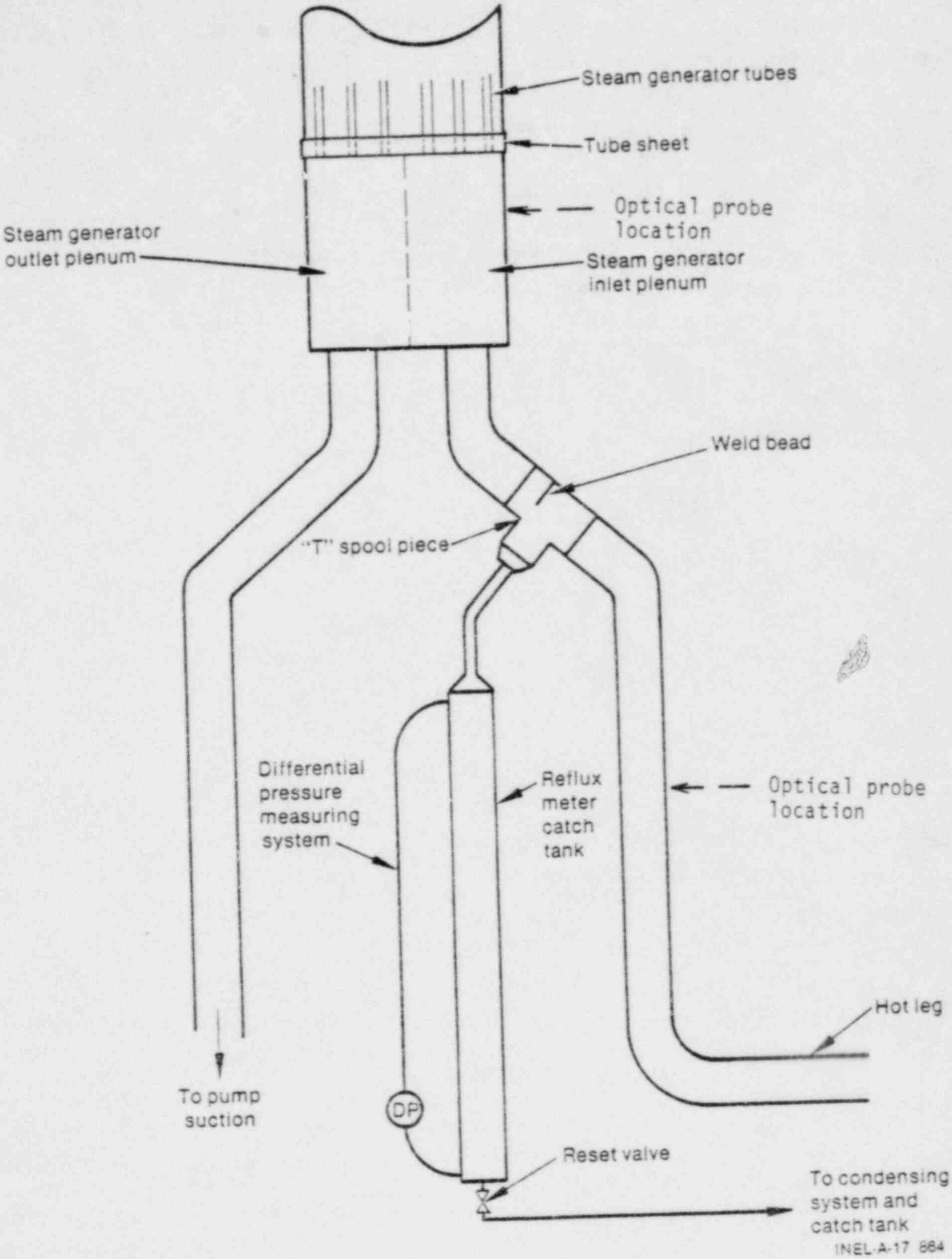

Figure 6. Reflux meter configuration.

the system at the onset of system drain. Therefore, the system mass inventory is referenced to a full system minus the pressurizer fluid. The pressurizer was used only to establish initial conditions. After the reflux natural circulation mode was established the secondary side collapsed liquid level was varied to examine the effect of steam generator secondary conditions on the natural circulation flow rate. Table 1 presents a condensed list of significant events for Test S-NC-4.

A total of 12 flow rate measurements were obtained for Test S-NC-4.[a] These consisted of 7 direct measurements of reflux using the reflux meter and 5 measurements of carryover.[b] For measurements with the reflux meter some liquid was removed from the system by draining. After each measurement liquid was injected from a heated tank in order to re-establish the primary system mass inventory. Carryover measurements were accomplished by closing the valve in the intact loop pump replacement spool causing water to accumulate in the vertical piping between the steam generator outlet and the pump suction. Differential pressure cells were used to measure the liquid accumulation and thus infer mass flow rate. Since this method removed no mass from the system it was necessary only to open the valve to re-establish system conditions.

Data was taken for both 30 kW and 60 kW core power. The steam generator secondary side collapsed liquid level was varied in 5 increments from full (tubes covered) to 255 cm above the tube sheet. The secondary side pressure was kept constant at 6.0 MPa. Figure 7 presents an idealized sequence of events for the controlled parameters. Data was taken continuously for all cases and between cases when conditions were being re-established.

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a. Eight other single-phase and two-phase points were obtained while draining the system to achieve conditions for Test S-NC-4. These will be reported in the Experimental Data Report for the test.

b. Carryover is defined here as the liquid which is condensed in, or carried-over to, the downflow side of the steam generator tubes, consequently flowing to the pump suction.

TABLE 1. SEQUENCE OF SIGNIFICANT EVENTS FOR TEST S-NC-4

Time (min)	Event
0	Data acquisition started (real time = 12:44:24).
11 to 137	Performed 7 drains from vessel lower plenum to reduce inventory and induce reflux conditions. 60 kW core power. Full steam generator secondary.
162 to 176	Reflux meter drain and measurement.
184 to 192	Inject liquid from heated accumulator.
196	Drain steam generator to 818 cm collapsed level.
239 to 241	Reflux meter drain and measurement.
250 to 259	Inject liquid from heated accumulator.
256	Reduce core power to 30 kW.
265 to 270	Reflux meter drain and measurement.
297 to 304	Inject liquid from heated accumulator.
308 to 311	Close pump replacement spool valve and take reflux carryover measurement.
335 to 342	Inject liquid from heated accumulator.
312	Increase core power to 60 kW.
320 to 322	Close pump replacement spool valve and take reflux carryover measurement.
326	Drain steam generator to 749 cm collapsed level.
352 to 361	Reflux meter drain and measurement.
384	Drain steam generator to 652 cm collapsed level.
372 to 397	Inject liquid from heated accumulator.
406 to 412	Reflux meter drain and measurement.
416 to 428	Inject liquid from heated accumulator.

TABLE 1. (continued)

Time (min)	Event
436 to 441	Close pump replacement spool valve and take reflux carryover measurement.
443	Reduce core power to 30 kW.
449 to 456	Close pump replacement spool valve and take reflux carryover measurement.
457	Drain steam generator to 452 cm collapsed level.
462 to 471	Close pump replacement spool valve and take reflux carryover measurement.
470	Increase core power to 60 kW.
486	Reduce core power to 30 kW.
498 to 501	Reflux meter drain and measurement.
508 to 513	Inject water from heated accumulator.
513	Drain steam generator to 224 cm collapsed level.
541 to 546	Reflux meter drain and measurement.

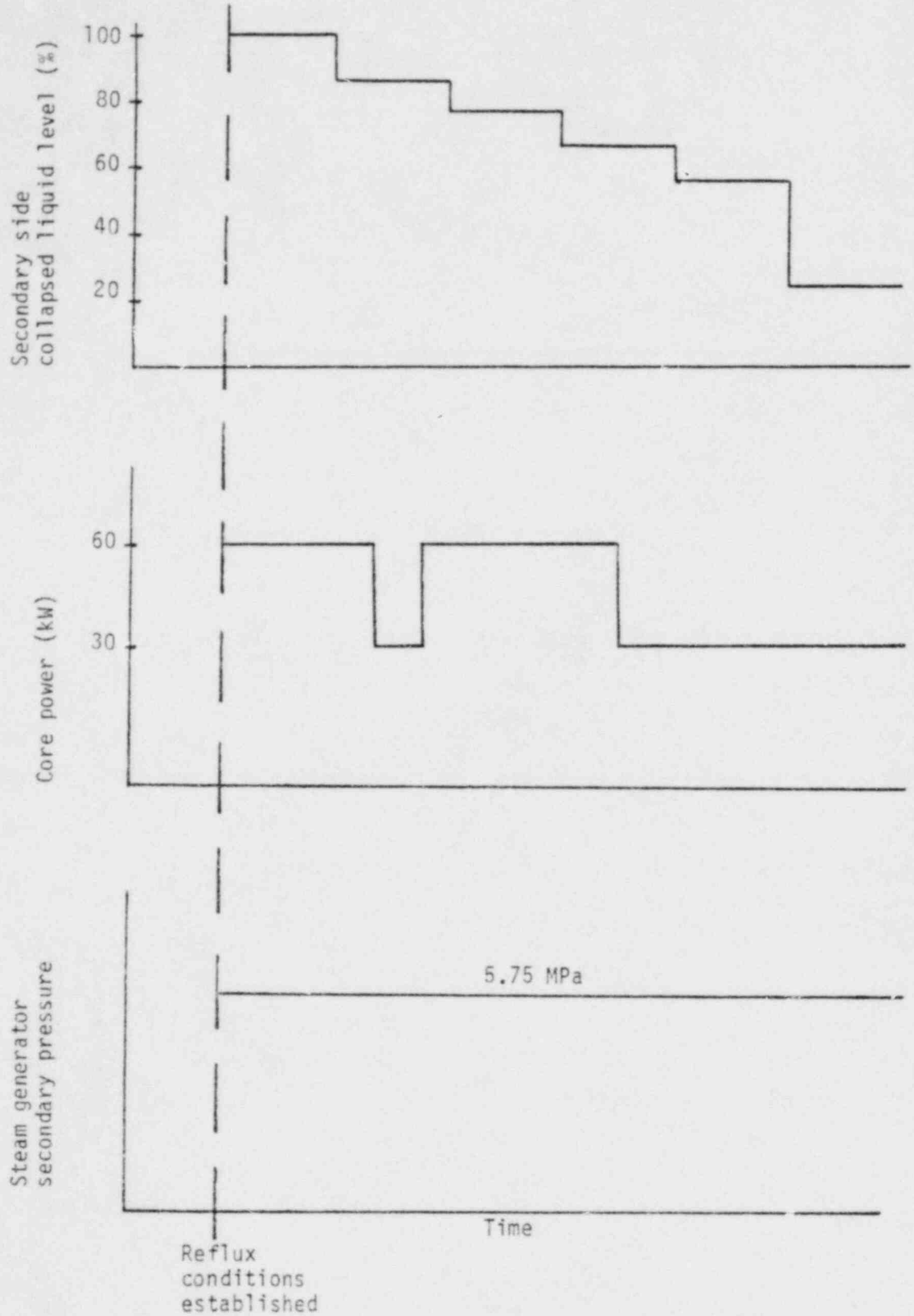

Figure 7. Idealized sequence of events for Test S-NC-4.

External heaters were used to make up heat loss during the entire experiment. Due to the extensive system voiding that occurs during reflux conditions, it was necesary to reduce the external heater power below that required to totally offset the heat loss to ambient (as determined from heat loss characterization testing) in order to prevent excessive pressure boundary temperatures. Power to the vessel/downcomer heaters was approximately 8 kW lower than the estimated loss while power on the cold leg and pump suction was approximately 1.5 kW low. These differences should be taken into consideration when analyzing and modeling the experiment.

3. TEST RESULTS

Results from Test S-NC-4 are presented in the following sections. The major variables for Test S-NC-4 were the core power and the secondary side collapsed liquid level. The main objective of the test was to examine the effect of the secondary side fluid inventory on the reflux cooling mode of natural circulation. Presented first is a discussion of data points obtained for the various steady-state conditions. Next a typical reflux cooling mode is examined in terms of fluid temperature and mass distribution in the system, followed by an examination of the effect of secondary liquid level on reflux cooling.

3.1 Summary of Data Points for Test S-NC-4

A total of 12 steady-state reflux cooling conditions were achieved. Controlled test variables were the core power, primary mass inventory, and the secondary liquid level. The core powers were 31.4 kW and 60.9 kW and the secondary collapsed liquid level varied between 100% of the U-tube height to 24%. Although the system mass inventory was not a major test parameter, it varied from one steady-state point to another as described in Section 2.3. It was determined that primary system mass inventory was not a significant parameter and little effect of system mass inventory on reflux was observed as long as the core was adequately covered with coolant.

Test conditions and important system steady-state parameters for the 12 data points are presented in Table 2. The required primary system mass inventory for conducting the test was determined by draining mass until visual observations by optical probes showed the reflux cooling mode, i.e., continuous vapor with liquid fall back in the steam generator inlet plenum and in the hot leg near the steam generator inlet. For this test, when the mass inventory was decreased to 64.4% at 60.9 kW core power, the hot leg was entirely voided and reflux was visually observed.

TABLE 2. TEST CONDITIONS FOR S-NC-4[b]

Number	Primary Pressure (MPa)	Core Inlet Temperature (K)	Core Outlet Temperature (K)	Core Power (kW)	Steam Generator Conditions: Pressure (MPa)	Steam Generator Conditions: Liquid Level (m)	Steam Generator Conditions: Heat Transfer Area (%)
1	6.2	540	550	60.9	5.72	10.67	100
2	6.2	539	550	60.9	5.74	8.18	89
3	6.1	530	549	31.4	5.74	8.18	89
4	6.1	545	549	31.4	5.74	8.59	93
5	6.2	540	567~596[a]	60.9	5.74	8.59	93
6	6.2	535	550	60.9	5.74	7.49	81
7	6.2	535	551	60.9	5.75	6.52	71
8	6.4	550	552	60.9	5.75	6.52	71
9	6.2	548	551	31.4	5.75	6.52	71
10	6.2	548	550	31.4	5.76	4.52	49
11	6.2	538	550	31.4	5.76	4.52	49
12	6.9	535	558	31.4	5.79	2.24	24

a. The core was partially uncovered.

b. The external heaters were operated to compensate for system heat loss as shown below:

Number	Vessel	Hot Leg	Cold Leg	Pump Suction
1	18.5	4.8	1.0	4.0
2	18.5	4.8	2.0	5.0
3	17.2	4.8	2.0	5.0
4,5	16.0	4.8	2.0	5.0
6	16.5	4.8	2.0	5.0
7~12	15.5	4.8	2.0	5.0

During the test, the steam generator secondary fluid was drained in discrete steps. Core power was varied between 31.4 kW and 60.9 kW to examine the effect of core power on the reflux cooling mode. The reflux meter was used to measure the refluxing rate in the upflow side of the U-tubes and a valve and differential pressure measurements were used to quantify the carryover rate in the downflow side of the U-tubes. Among the 12 data points, seven data points were of the refluxing rate measurement and five data points were for the carryover rate measurement. During the refluxing rate measurements, the system mass inventory decreased since the refluxing fluid was diverted into the reflux meter and did not flow back to the core. However, system mass change during the measurements did not exhibit any significant effect on the reflux cooling mode. This is apparent from Figure 8 which shows the calculated reflux rate over the time period for a measurement.

As shown in Table 2, the fluid temperature at the core inlet was subcooled due to the colder water injected into the cold leg from the accumulator between measurements to makeup the mass depletion from the reflux meter drain. The effect of the subcooled conditions at the core inlet was to slightly decrease the steam generation rate in the core since part of the core power was consumed to heatup the subcooled water to saturation. However, it was estimated that only 2% to 5% of the total core power was used for sensible heating and the rest of the core power contributed to steam generation and the effect, therefore, was relatively minor.

3.2 Fluid Mass and Temperature Distribution in the System During Reflux Cooling

Reflux cooling in a nuclear reactor is defined as the core cooling mechanism that removes core decay heat in such a way that a portion of the steam generated in the core is condensed in the steam generator and this condensed liquid flows back into the core through the hot leg. Due to the lack of experimental data involving an integral test facility simulating a nuclear reactor, there has been much speculation about this mechanism and

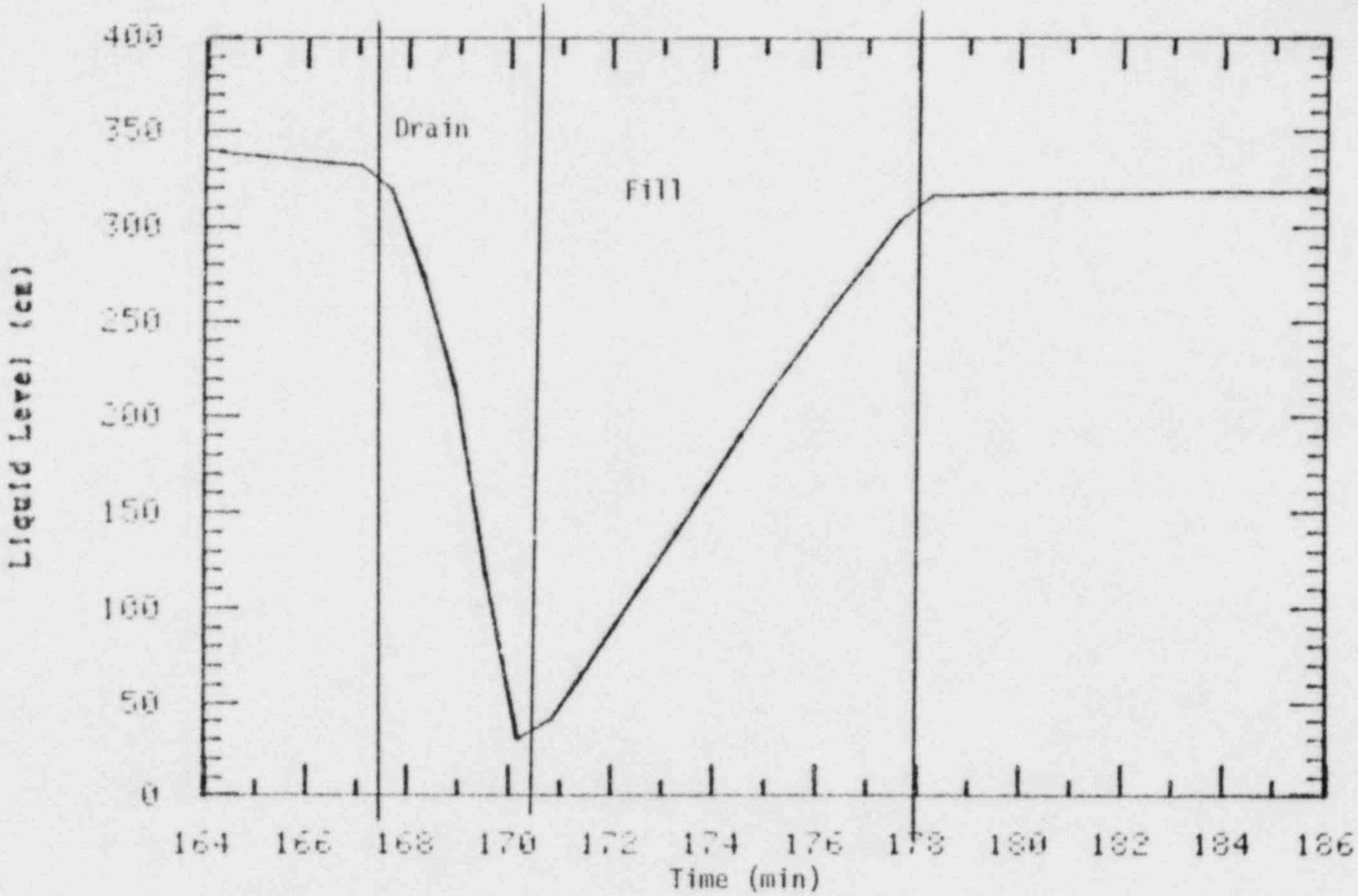

Figure 8. Typical reflux meter drain and fill.

its effectiveness for cooling. One of the major objectives of the Semiscale natural circulation test series is to clarify these speculations by performing steady-state reflux tests and quantifying the rate of reflux through the use of the reflux meter. Visual observation by the optical probes of the reflux phenomenon is also a powerful tool for verifying the existence of reflux cooling.

Presented in this section are results of the preliminary analysis of the mechanism of reflux natural circulation based upon the test results of S-NC-4. As described in Section 3.1, 12 data points were obtained with various conditions. In this section, the first data point is used to describe the mechanism of the reflux cooling mode as a typical reflux case. It was found that the basic cooling mechanism was the same for all of the data points.

Figure 9 illustrates the fluid mass distribution and temperature distribution in the system for the first data point. It was known from previous test results of S-NC-2[4] that to insure a reflux cooling mode, the system mass inventory must be low enough so that the hot leg is entirely voided. Otherwise the cooling mode is classified as two-phase natural circulation. In the present test, the collapsed liquid level in the vessel was approximately 0.5 m below the top of the heated section of the core. It was estimated from the data that the top portion of the core was covered with two-phase mixture and never uncovered in this case. Heater rod temperatures and fluid temperatures in the core indicated that a subcooled fluid entered the core and became saturated within approximately 40 cm from the bottom of the heated section. This contributes to 5% of the total core power going into sensible heating . Additionally, it was not possible to completely offset the heat losses in the vessel/downcomer with external heaters. Heat loss from the downcomer and lower plenum is reflected in the subcooling at the core inlet. The net heat loss from the vessel core region is estimated to be on the order of 3 to 4 kW. This will also reduce the effective steaming rate from the core about 5% for the 60 kW cases and 10% for the 30 kW. Therefore, the effective steam generation rate in this case was approximately 0.035 kg/s corresponding to 90% of core power (60.0 kW).

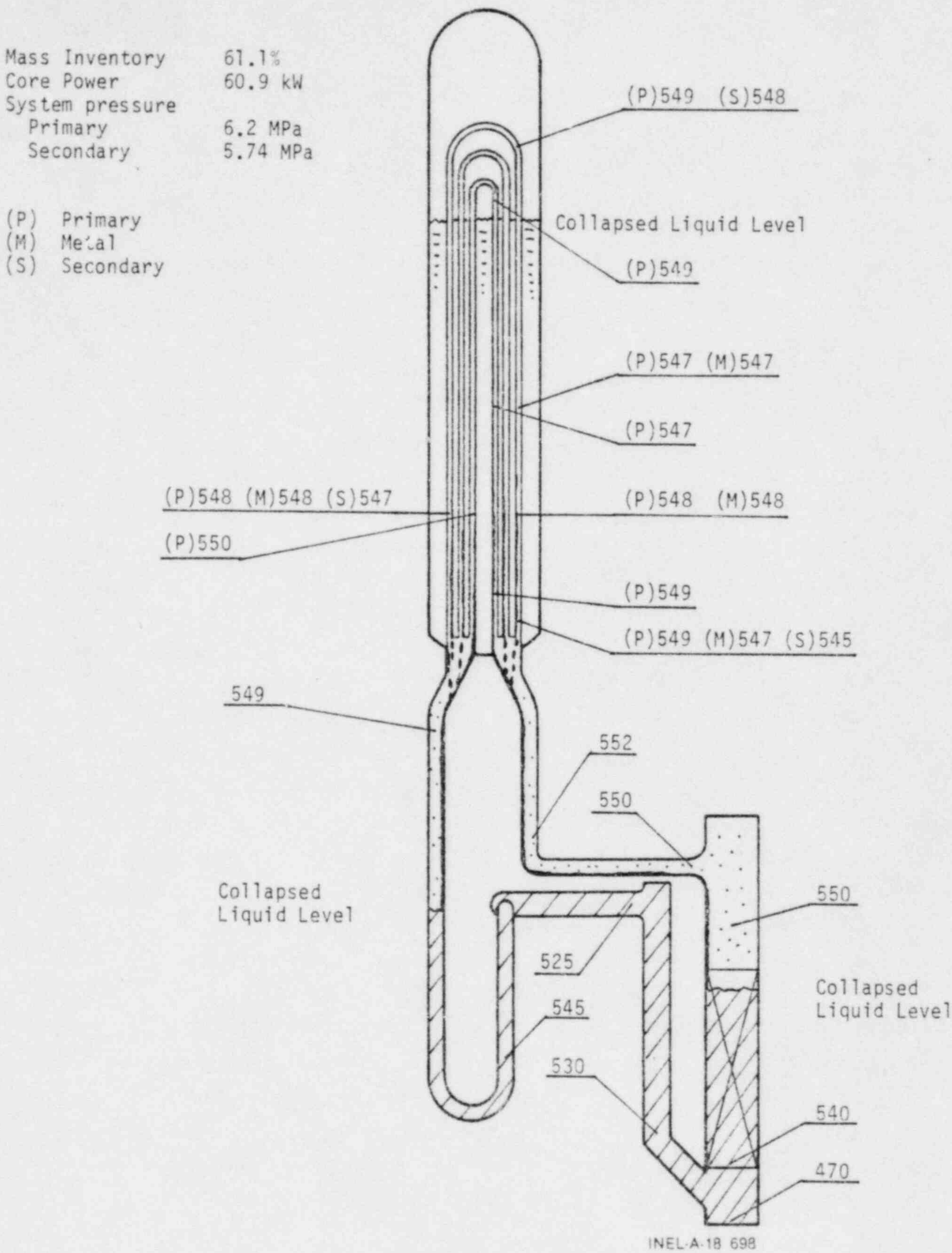

Figure 9. Fluid temperature and mass distribution in the system during reflux natural circulation.

The steam generated in the core flowed through the hot leg and into the steam generator where the steam was condensed in both the upflow side of the U-tubes and the downflow side of the U-tubes. The primary and secondary fluid temperatures in the U-tubes and the metal temperatures of the U-tubes showed that the condensed steam was further cooled down by heat transfer to the secondary coolant and subcooled liquid flowed to the plena on both sides of the steam generator.

The liquid that flowed through to the steam generator outlet side was collected in the loop seal. The collapsed liquid level in the downflow side of the pump suction piping remained at approximately cold leg elevation during steady-state conditions; decreasing when liquid was removed from the system during reflux meter measurements. The differential pressure measurements and the density measurement in the cold leg indicated that the pump suction piping upflow side, the cold leg and the downcomer were liquid full. Therefore, the condensed steam in the downflow side of the steam generator was fed back into the lower plenum and the core via the cold leg. The liquid level in the loop seal remained manometrically balanced with the liquid level in the vessel to overcome the density difference between fluid in the loop seal and the vessel.

During the test, a heated accumulator was used to make-up system mass losses which resulted from the reflux meter drains. The injection was made into the cold leg so that the injected water could enter into the downcomer and the pump suction. Heat losses in the line between the accumulator and the system caused the water temperature to be well below the system temperature such that the fluid temperature in the downcomer stayed cool (3 to 15 K below saturation temperature) even though the external heaters were in operation to makeup heat loss. Therefore, the relative density of the fluid in the cold leg and in the downcomer was larger than what would have been observed if the fluid was at saturation conditions. Overall behavior would be expected to be the same since density gradient induced core flow is not a dominant mechanism in the reflux mode.

In summary, Test S-NC-4 showed that the reflux cooling mode does exist for system mass inventories low enough to cause hot leg uncovery. Within the time frame of the experiment duration, the reflux cooling mode was stable and a viable mode of core cooling.

3.3 Effects of Core Power and Secondary Liquid Level on Reflux Cooling

The effect of core power and secondary liquid level on reflux cooling have been examined by varying the core power from 31.4 kW to 60.9 kW and depleting the secondary coolant from covering 100% of the heat transfer area in the steam generator to 24%. Table 3 and Figure 10 present the reflux mass flow rates measured by the reflux meter in the hot leg and the carryover rates measured by closing the valve in the cold leg and collecting liquid in the pump suction. The measurements obtained with the reflux meter appear to be reasonably consistent, while those obtained for the carryover measurement exhibited a broader scatter. The scatter exhibited by the carryover measurements are a probable result of differences in pump suction liquid levels and oscillations in pump suction liquid inventories at the time of valve closure. Visual monitoring of the hot leg piping below the reflux meter T indicated that the collection efficiency of the reflux meter was nearly 100% at 30 kW core power and slightly lower at 60 kW core power. At this time the mass flows reported from the reflux meter measurement are considered to be most accurate.

Figure 11 presents the mass flows from Figure 10 in terms of efficiencies related to the theoretical boiloff rates. For the high power cases (60.9 kW), with tubes greater than 50% covered, 44% to 46% of the steam generated in the core was condensed in the upflow side of the steam generator and refluxed back, while in the lower core power cases (31.4 kW) 54% of the steam was condensed in the upflow side. This suggests that the condensation rate was influenced by the steam velocity in the U-tubes. A general trend exhibited in Figures 10 and 11 is that the reduction in

TABLE 3. REFLUXING RATE FOR S-NC-4

Number	Primary System Mass Inventory[a] Start of Measurement (%)	Primary System Mass Inventory[a] End of Measurement (%)	Effective Steaming Rate (kg/s)	Refluxing Rate: Carry-Over (kg/s)	Refluxing Rate: Carry-Over (%)[b]	Refluxing Rate: Reflux (kg/s)	Refluxing Rate: Reflux (%)[b]
1	58.5	48.1	0.035	--	--	0.0162	46
2	61.1	52.3	0.035	--	--	0.0154	44
3	60.7	53.8	0.017	--	--	0.0092	54
4	62.4	62.4	0.017	0.0101	59	--	--
5	62.4	62.4	0.035[b]	0.0116	33	--	--
6	64.4	51.9	0.035	--	--	0.0154	44
7	65.9	58.6	0.035	--	--	0.0158	45
8	71.7	71.7	0.035	0.0175	50	--	--
9	71.7	71.7	0.017	0.0127	75	--	--
10	71.7	71.7	0.017	0.0229	134	--	--
11	70.1	65.8	0.017	--	--	0.0092	54
12	69.9	63.2	0.017	--	--	0.0070	41

a. The system mass was 113 kg when full.

b. Percent of the effective steaming rate.

c. Steaming rate plus superheating rate.

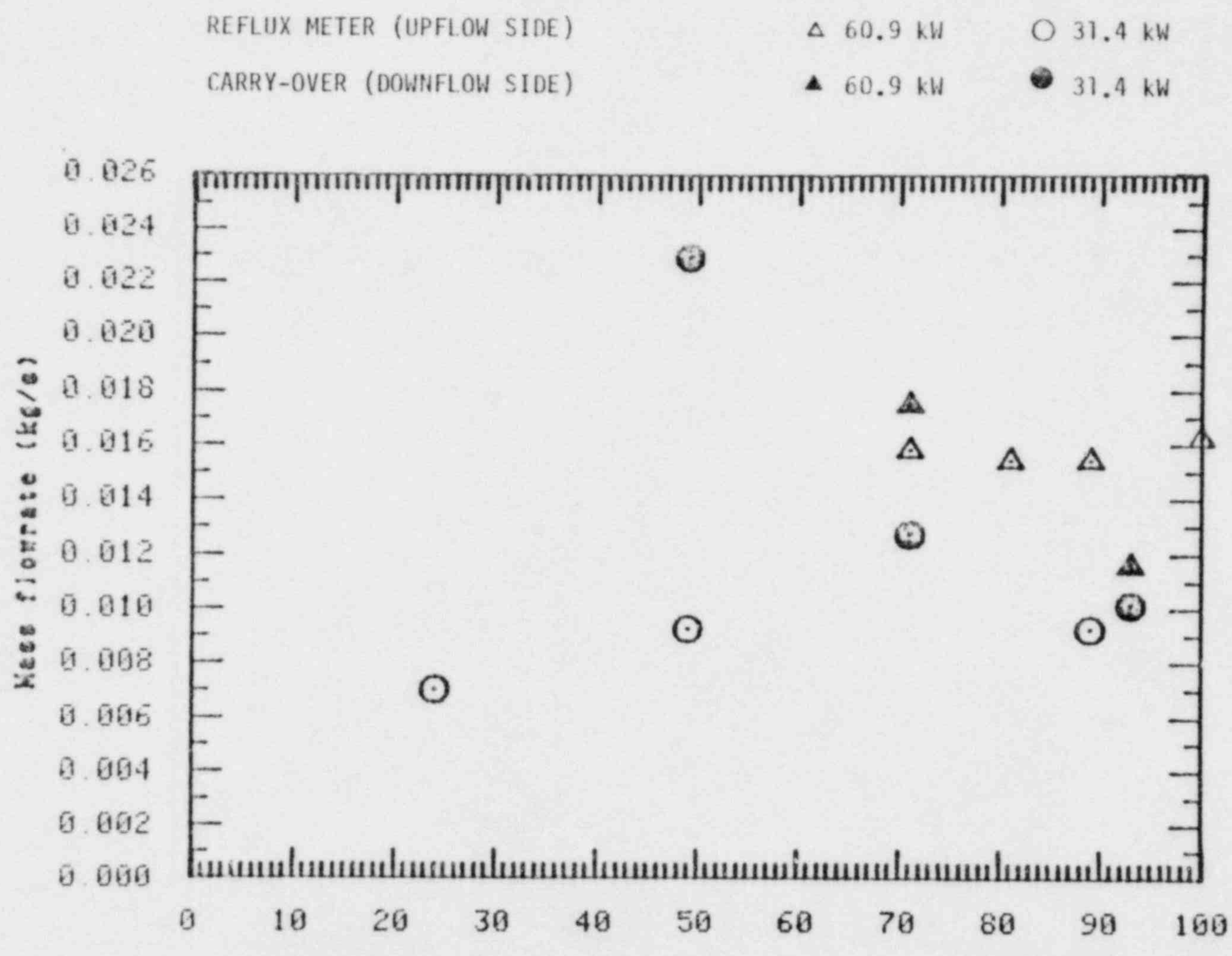

Figure 10. Reflux and carryover rates for Test S-NC-4.

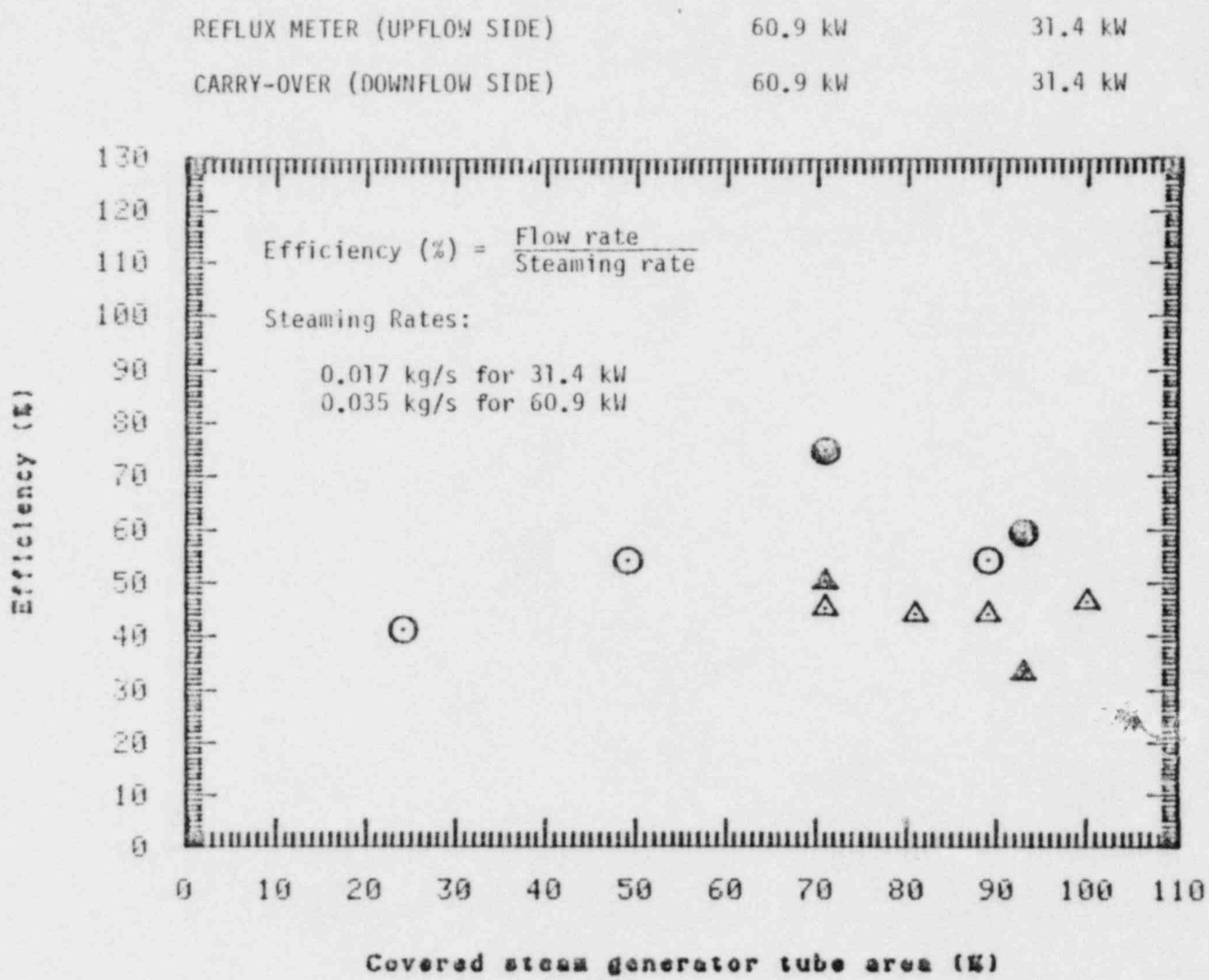

Figure 11. Reflux and carryover efficiencies for Test S-NC-4.

secondary side inventory[a] had no significant effect on reflux flow at inventories greater than about 50% for the low power case. The amount of carryover was observed to increase as secondary inventory decreased. But the decrease in reflux-to-carryover ratio was small relative to the large decrease in inventory. For the high power case (60.9 kW) all of data was taken at secondary inventories above 70%. When the secondary was drained to 50% or lower it was not possible to keep the core from drying out. Reasons for the dryout will be determined in further posttest analyses.

The primary system pressure was also found to be relatively insensitive to secondary level over the range examined. As seen in Table 2 the pressure remained approximately constant for all cases except for the last case at 24% secondary side level where it rose from 6.2 to 6.9 MPa.

In summary, most of the steam generated in the core was condensed in the steam generator and heat losses to ambient appeared to have little influence. The reflux-to-carryover flow split was found to be close to 1:1. This ratio was found to decrease only slightly as the secondary side inventory was reduced to 24%. Primary conditions (pressure and temperature) remained reasonably constant for secondary side inventories from full down to 24%, except for the 60 kW core power case (3% full power) where dryout occurred for secondary levels below 50%.

a. The data in Figures 10 and 11 are plotted vs covered tube heat transfer area. Covered heat transfer area is defined in terms of the calculated collapsed liquid level in the secondary side. This concept is a convenience and does not imply that such a condition exists in the secondary.

4. COMPARISON OF DATA TO PRETEST CALCULATION

A comparison of Test S-NC-4 data to the results of the pretest calculations[5] is presented in this section. The pretest calculations were performed with the RELAP5/MOD1 computer code (Version 9). The system model used in these calculations is described in Appendix A. Test S-NC-4 provided data on reflux natural circulation and the comparisons presented in this section provide a basis for evaluating the capability of the present analytical model to predict these modes of natural circulation.

Presented in Table 4 is a summary of the measured and calculated steady-state parameters for Test S-NC-4. The principal differences between the test and calculations were in the resultant natural circulation modes for given conditions. Steady-state reflux natural circulation was not calculated to occur although it was observed during the test. From the calculations it was determined that the vapor velocities in the steam generator tubes exceeded the flooding threshold velocity which prevented condensate fall back into the hot leg. The failure to predict reflux is, in part, believed to be caused by an inadequacy in the RELAP5 code. The present RELAP5 vapor generation model does not account for wall heat transfer. Consequently, the steam condensation rate and therefore the liquid mass distribution along the upside of the steam generator tubes was under predicted. The wall heat transfer problem will be resolved during the posttest analysis effort.

In addition, during the test subcooled makeup was injected into the cold leg and environmental heat losses from the cold leg and downcomer were not totally offset with the external piping heaters. In the prediction the environmental heat losses were assumed to be zero and no makeup was modeled such that the entire primary system temperature distribution was uniform and close to saturation conditions. These differences resulted in measured core differential temperatures that were significantly larger than the calculated values.

TABLE 4. MEASURED AND CALCULATED SYSTEM PARAMETERS FOR STEADY-STATE TEST CONDITIONS[a]

		Case 2	Case 5	Case 6	Case 8
Primary System Pressure (MPa)	Measured	6.2	6.2	6.2	6.4
	Calculated	6.4	6.4	6.4	6.5
Core Differential Temperature (K)	Measured	11	27-56[a]	15	2
	Calculated	0.5	0.5	0.5	0.5
Hot leg Temperature (MPa)	Measured	550	567-596[b]	550	552
	Calculated	553	553	553	553
Secondary Pressure (MPa)	Measured	5.72	5.74	5.74	5.75
	Calculated	6.00	6.00	6.00	5.00
Secondary Liquid Level (m)	Measured	8.18	8.59	7.49	6.52
	Calculated	8.53	8.53	7.62	6.58
Core power (kW)	Measured	60.9	60.9	60.9	60.9
	Calculated	60.0	60.0	60.0	60.0

a. Cases correspond to those of Table 2.

b. Note core was partially uncovered.

There was generally good agreement between the calculated and measured primary system pressures and hot leg temperatures for the same approximate secondary side conditions.

5. CONCLUSIONS

A total of 12 measurements were obtained of steady-state reflux mass flow and carryover mass flow for a variety of steam generator secondary levels and core powers of 30 kW and 60 kW.

The reflux-to-carryover flow split was found to be approximately 1:1.

Reduction of secondary side collapsed liquid level from 100% to 50% of equivalent tube covered surface area exhibited virtually no effect on the reflux-to-carryover split nor the primary pressure and temperatures. At 24% secondary level a small decrease in the reflux flow split was measured and a small increase in primary pressure.

The core was observed to dryout for a core power of 60 kW and secondary liquid level of 50% or lower. The core remained cooled at a power of 30 kW (1-1/2% full power).

RELAP5/MOD1 predictions failed to predict a steady-state reflux cooling mode. Suspected inadequancies within the code with regard to flooding and condensation heat transfer will be reviewed in posttest analyses. There was generally good agreement between predicted and measured primary pressures.

6. REFERENCES

1. G. G. Loomis, K.Soda, "Experiment Operating Specification for the Natural Circulation Test Series (Series NC) Semiscale Mod-2A EGG-SEMI-5427, April 1981.

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3. K. Soda, letter to D. J. Shimeck, "A Proof of Principle Test of the Reflux Meter", KS-5-81, April 15, 1981.

4. P. North, letter to R. E. Tiller, "PN-81-81, Transmittal of Quick Look Report for Semiscale Mod-2A Natural Circulation Test S-NC-2, July 13, 1981.

5. P. North, letter to R. E. Tiller, "PN-73-81, Test Predictions for the Water Reactor Research Test Facilities Mod-2A Natural Circulation Tests S-NC-3 and S-NC-4", July 21, 1981.

APPENDIX A

The pretest prediction for Semiscale Mod-2A Test S-NC-4 was performed using Verison 9 of the RELAP5/MOD1 computer code (Idaho National Engineering Laboratory Configuration Control Number F00316). The input deck for the S-NC-4 calculations is stored under the INEL configuration control number F00351. The model nodalization diagram used for the calculation is shown in Figure A-1. The model consists of 143 hydrodynamic volumes and 78 heat structures. Heat transfer to the environment from the primary and secondary system was assumed to be zero. All volume and junction parameters are calculated with nonequilibrium and nonhomogeneous code models.

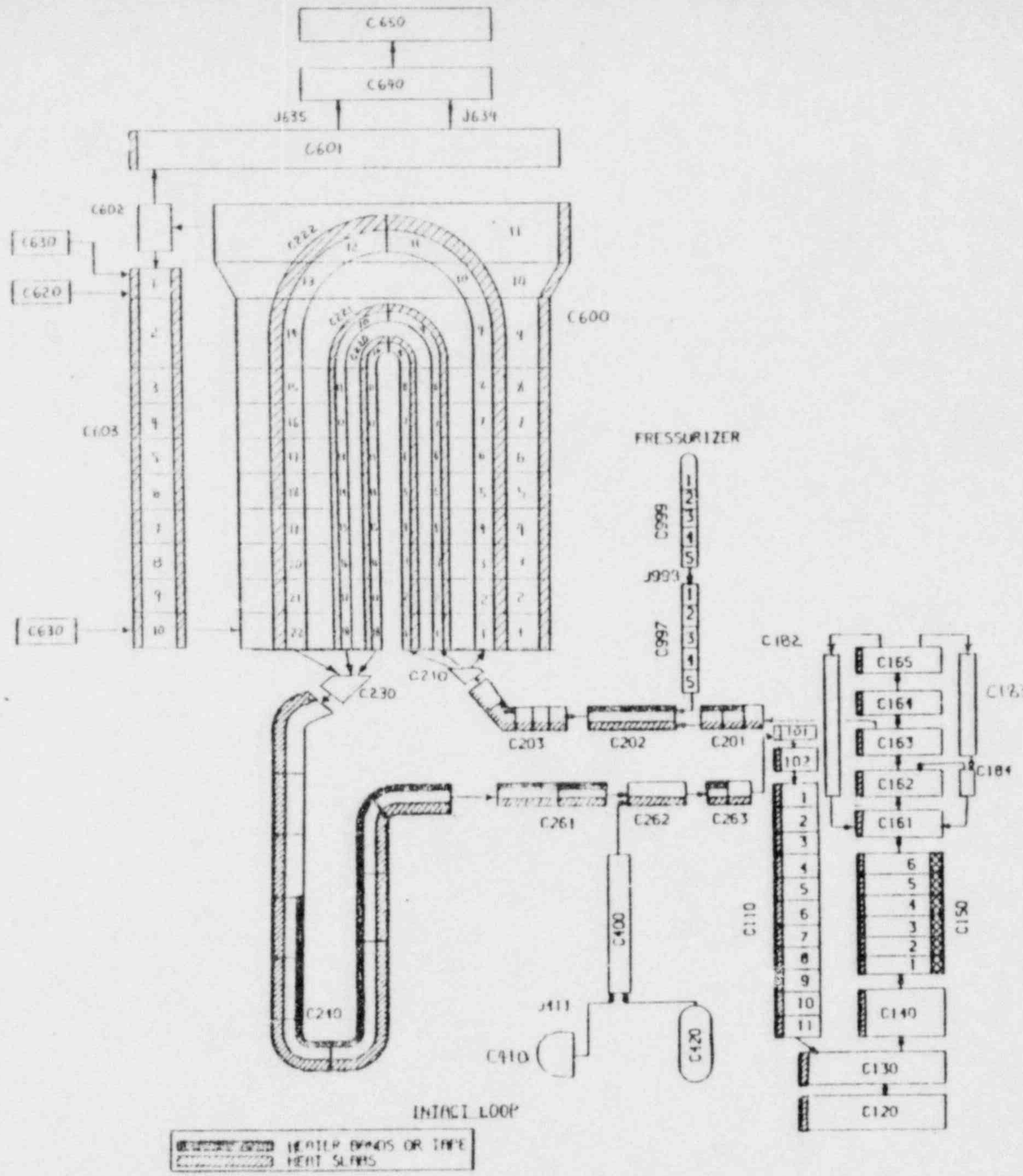

Figure A1. RELAP5 model nodalization diagram.