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ADVANCED TWO-PHASE FLOW INSTRUMENTATION PROGRAM QUARTERLY PROGRESS REPORT FOR APRIL–JUNE 1980

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ADVANCED TWO-PHASE FLOW INSTRUMENTATION PROGRAM
QUARTERLY PROGRESS REPORT FOR APRIL–JUNE 1980

K. G. Turnage R. L. Anderson*
C. E. Davis G. N. Miller*

ABSTRACT

Work performed to develop and evaluate liquid level sensors for in-vessel use in pressurized water reactors is described. Experiments were performed with three thermal-type level sensors in natural convection to saturated water and steam. Pressures in those tests ranged from 0.1 to 8.6 MPa (15 to 1250 psia). Thermal-type sensors were also tested in steam-water forced convection at low and moderate pressures. Sensor response was found to be insensitive to flow velocity and void fraction but sensitive to the presence or absence of a liquid phase.

A series of meetings was held with representatives of three pressurized water reactor vendors regarding research goals and implementation of reactor-vessel level monitoring instrumentation.

I. INTRODUCTION

During the accident at the Three Mile Island (TMI) nuclear power plant, a condition of low water level in the reactor vessel and inadequate core cooling existed and was not recognized for a long period of time. A review of the accident was conducted by the U.S. Nuclear Regulatory Commission (NRC) TMI-2 Lessons Learned Task Force.[1] Their report recommended that improved instrumentation systems, including reactor-vessel liquid level (coolant) sensors, be developed and implemented in all pressurized water reactors (PWRs) in the United States. Coolant sensors are intended to provide an unambiguous indication of the adequacy of core cooling. They must survive in accident conditions, and they must work under both natural and forced convection flow conditions.[2]

The Advanced Two-Phase Flow Instrumentation (ATPI) Program at Oak Ridge National Laboratory (ORNL) has been funded by the U.S. NRC Division of Reactor Safety Research to evaluate instrumentation systems for this purpose. As part of this effort, two concepts are being pursued concurrently: (1) thermal-type sensors, such as heated junction thermocouples (HTCs), and (2) acoustic sensors. Test sensors are being designed and fabricated at ORNL and procured from outside sources. A variety of tests are being run to evaluate the devices for power reactor use.

The experiments simulate thermal and hydraulic conditions believed to be typical of a postulated PWR loss-of-coolant accident (LOCA); both

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natural convection (reactor coolant pumps off) and forced convection (pumps on) two-phase flow tests have been run. The goals are to optimize the design of coolant sensors and to determine whether conditions exist under which ambiguous readings might occur. Generally, the test sequence for a particular device proceeds from static (covered-uncovered) tests at room temperature to static tests in saturated steam and water at elevated pressures and then to forced convection tests at relatively severe pressure, temperature, and flow rate conditions.

2. THERMAL DEVICES

Thermal devices being tested use pairs of K-type (Chromel vs Alumel) thermocouples (TCs) or resistance temperature detectors (RTDs) to sense the cooling capacity of the medium surrounding the device. One of the TCs is heated by an electric current passed through a separate wire; the other is primarily influenced by the fluid temperature. The difference between the temperatures of the heated and unheated points (ΔT) is monitored to compensate for variations in the system's fluid temperature. For a given heated power with good cooling conditions (liquid or rapidly flowing two-phase mixtures), the ΔT is relatively low; with poor heat transfer (e.g., stagnant steam), the temperature at the heated junction increases greatly, making the ΔT higher.

During the current report period, several thermal-type liquid level (coolant) sensors were tested at ORNL under varying conditions of temperature, pressure, and void fraction. The probes tested included two ORNL-fabricated HTCs, two HTC probes borrowed from the U.S. Navy, and a commercially available heated RTD sensor.

2.1 Natural Convection Tests

As reported previously,[3] the pressure vessel used for natural convection testing of liquid level sensors was modified to remove a number of internal components and to accommodate additional test sensors.

At the beginning of this period, the modified vessel was replaced in the Transient Instrument Test Facility (TITF), and hydrostatic pressure tests of the system to 15 MPa (2200 psia) were successfully completed. Three thermal-type level sensors were installed (Fig. 1), and testing was begun.

For level probe testing, the TITF is pressurized using strip heaters on the pressurizer body. Then, the level sensors are covered and uncovered with saturated water using system letdown valves and a high-pressure injection pump. An accurate measurement of the liquid level in the pressurizer is obtained independently of the test sensor by using a differential pressure transducer.

2.1.1 HTC ORNL I

Tests of an ORNL-fabricated sensor will be summarized first. The test sensor (ORNL I), described in a previous quarterly report,[4] incorporates both heated and reference TC junctions in a single sheath. For current tests, the probe was inserted horizontally through a fitting in the side of the pressure vessel (Fig. 1). Note that the hood or covering in place over the probe in earlier testing was no longer present for these tests. For each test point, a constant dc voltage was applied to the 6.5-Ω probe heater. Differential TC output voltages were obtained with heater currents ranging from 400 to 2800 mA. A digital voltmeter and a continuous chart recorder were used to record the output signal during testing.

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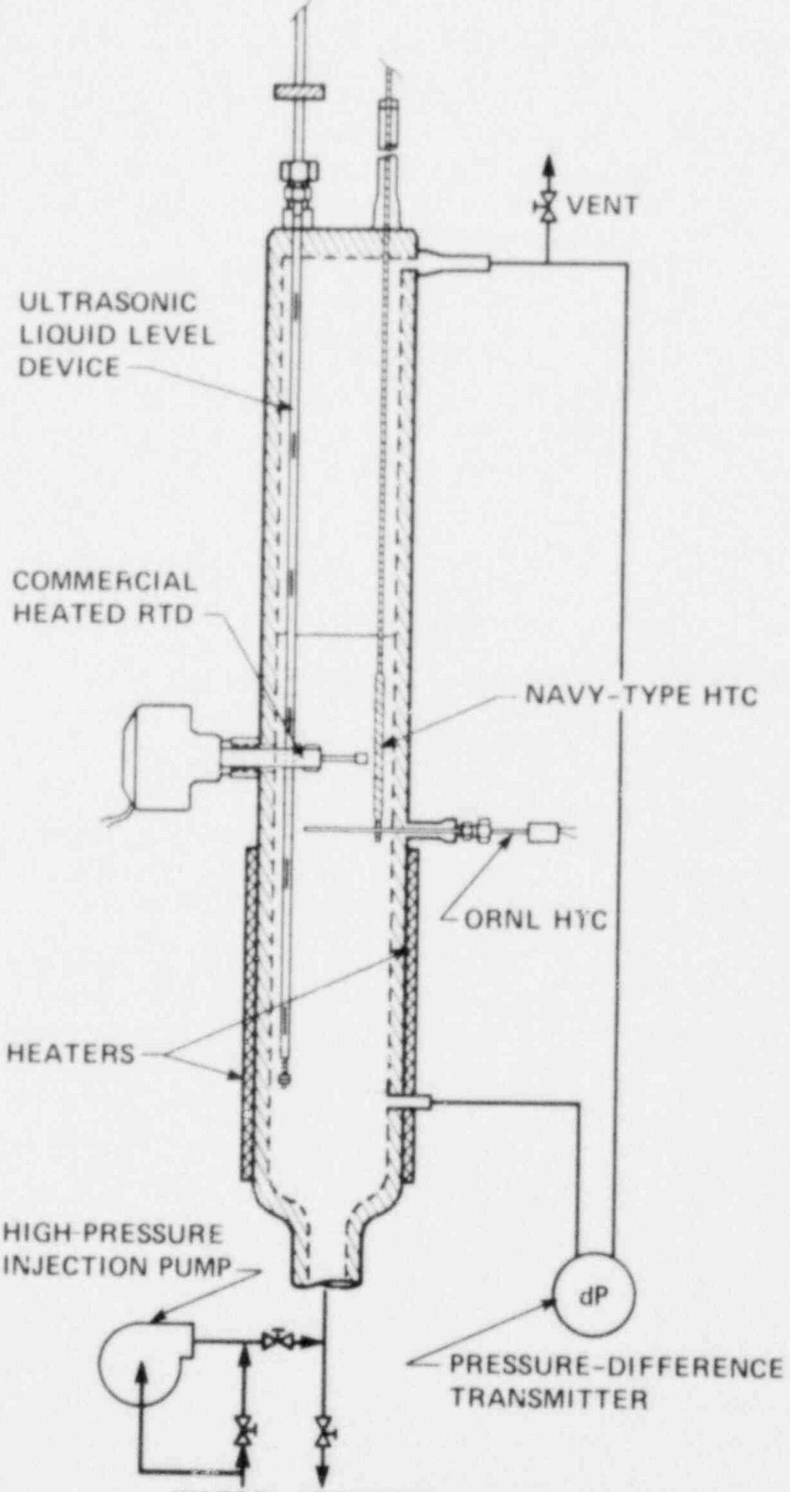

Fig. 1. Schematic of test section used for high-pressure natural convection experiments with thermal and acoustic liquid level sensors.

[The outside diameter of this probe was 3.5 mm (0.14 in.), and its heated length was 2.5 cm (1 in.). At the maximum heater current of 2.8 A, the steady-state surface heat flux, assuming no axial conduction, would be ~18 W/cm^2 (116 W/in.^{2}). This exceeds the steady-state surface heat flux of ~13 W/cm^2 (80 W/in.^{2}) from a 1.0-cm-diam nuclear fuel pin at maximum decay heat power levels.]

Figure 2 shows the ΔTs recorded from the ORNL I HTC as a function of heater power with system pressure (at saturated conditions) and surrounding medium (liquid or vapor) as parameters. Each data point represents a mean ΔT reading obtained after the TC output reached a steady-state value.

At a given heater current, the data show that steady-state ΔTs recorded when the test sensor was immersed in saturated steam were always greater than ΔTs recorded when the probe was covered with liquid. The sequence of curves at successively higher ambient pressures and temperatures shows that changes in ΔT from covered to uncovered states decrease with increasing pressure. This decrease is largely due to the improvement in natural convection heat transfer to saturated steam at higher steam pressures and densities.

The ΔTs recorded by the differential HTC are not an accurate measurement of the ΔT between the probe surface and the bulk fluid. There are at least two reasons for this: (1) There may be considerable axial heat conduction along the probe, particularly when the surface heat transfer coefficient is low. The reference junction may then be heated considerably by the heater. [The decrease in slope of the ΔT vs power curve at ΔTs above 300°C (Fig. 2) is probably due to this effect.] (2) When the surface heat transfer coefficient is high, there may be a relatively large ΔT between the centerline of the probe under the heater, where the HTC junction is located, and the surface temperature outside the heater. Thus, differential output from such a probe may be used to establish the order of magnitude of the surface heat transfer coefficient but may not determine it accurately.

2.1.2 Navy-type HTC

Experiments were also performed in the TITF pressurizer with an HTC liquid level device obtained from the U.S. Navy. Mounted vertically in the pressurizer (Fig. 1), the probe is enclosed in a single sheath with heated and reference thermocouple junctions separated axiallly by 18 cm. The HTC junction was nearer the probe tip and lower in elevation than the reference junction. The probe diameter at the heater was 3.7 mm, and the heated length was 1.0 cm. The measured ΔT was recorded with the sensor covered with saturated water or steam, with heater powers ranging from 0.4 to 21 W and system temperatures ranging from 25 to 300°C.

Steady-state response curves for the Navy HTC probe are shown in Fig. 3. Methods of probe operation and data interpretation for the natural convection tests were like those used with the ORNL probe, as previously described. Again, a distinct difference in probe output existed, depending on whether the probe was immersed in liquid or vapor. A particular state (covered or uncovered) was defined such that all of the probe's heated portion was immersed in that phase. However, negligible change in probe output occurred as the liquid level rose from just above the heater past the reference junction.

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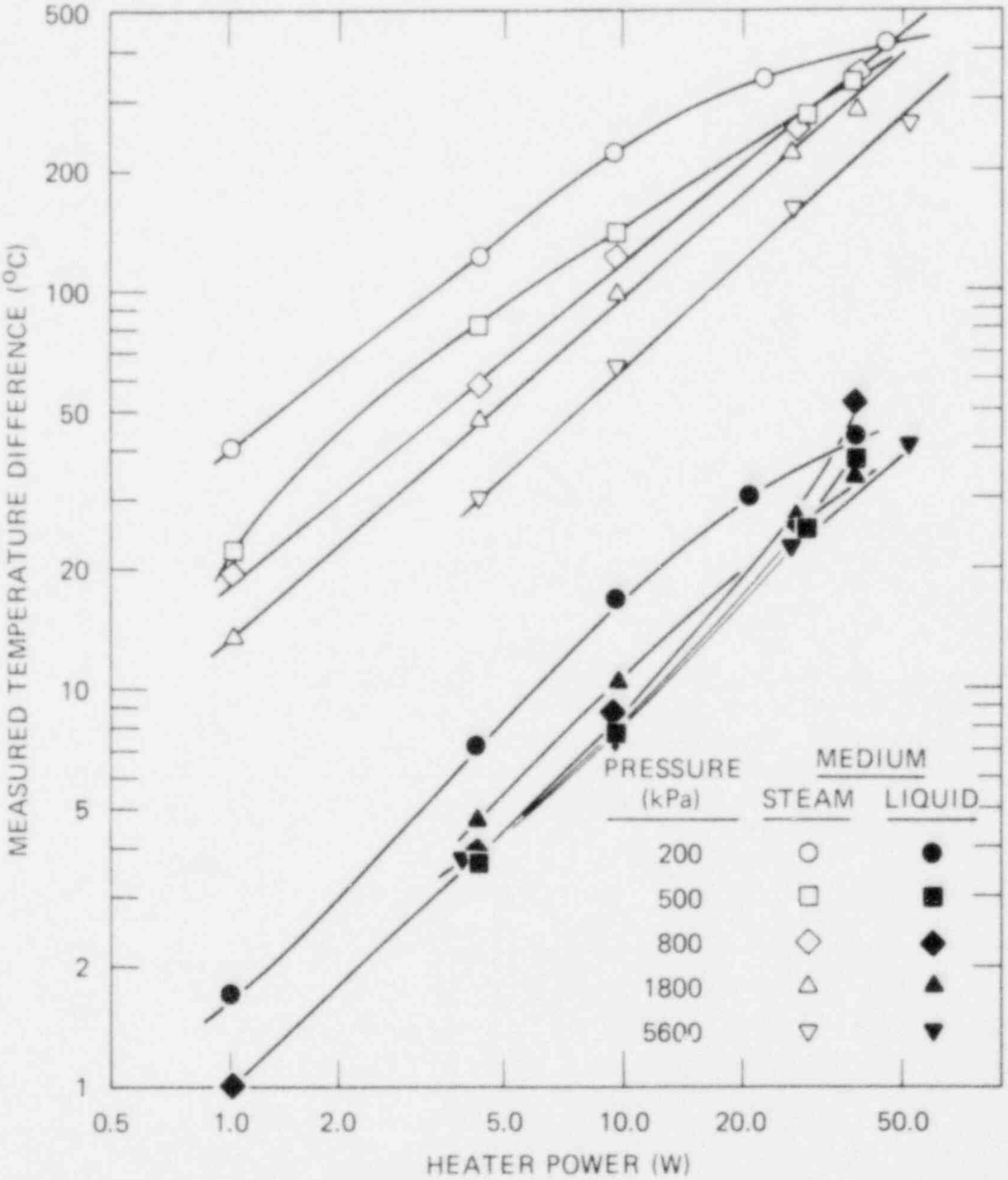

Fig. 2. Steady-state temperature differences recorded from HTC probe ORNL I in natural convection to saturated steam and water. Data are plotted vs power produced in probe heater with system pressure and medium surrounding probe as parameters.

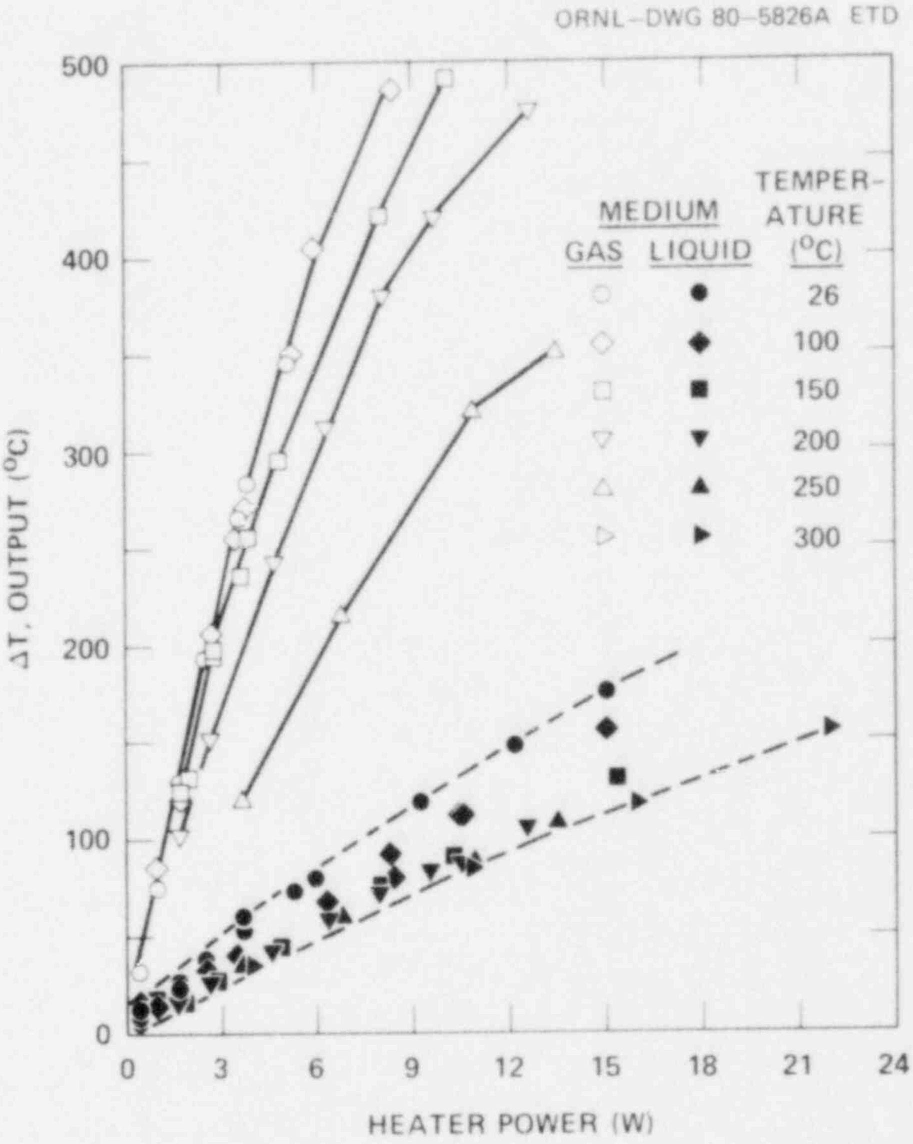

Fig. 3. Steady-state ΔTs recorded from Navy-type HTC sensor in natural convection to steam and water. Data are plotted vs power produced in probe heater with system temperature and medium surrounding probe as parameters.

A decrease in output ΔT with increasing ambient pressure and temperature was again observed for the vapor state (Fig. 3). The ΔT curves obtained in the covered state show less dependence on pressure than the vapor curves, but the reduction of observed ΔT at constant heater power and increasing pressure is in agreement with trends predicted by a widely used nucleate boiling heat transfer correlation.[5] However, a large variation existed in output ΔT while the probe was uncovered (Fig. 4). [The uncovered ΔTs (Fig. 3) represent the maximum ΔT observed at a given uncovered condition; this value was found to be fairly repeatable.] Figure 4 shows a ΔT output from this probe plotted vs time, while the ambient

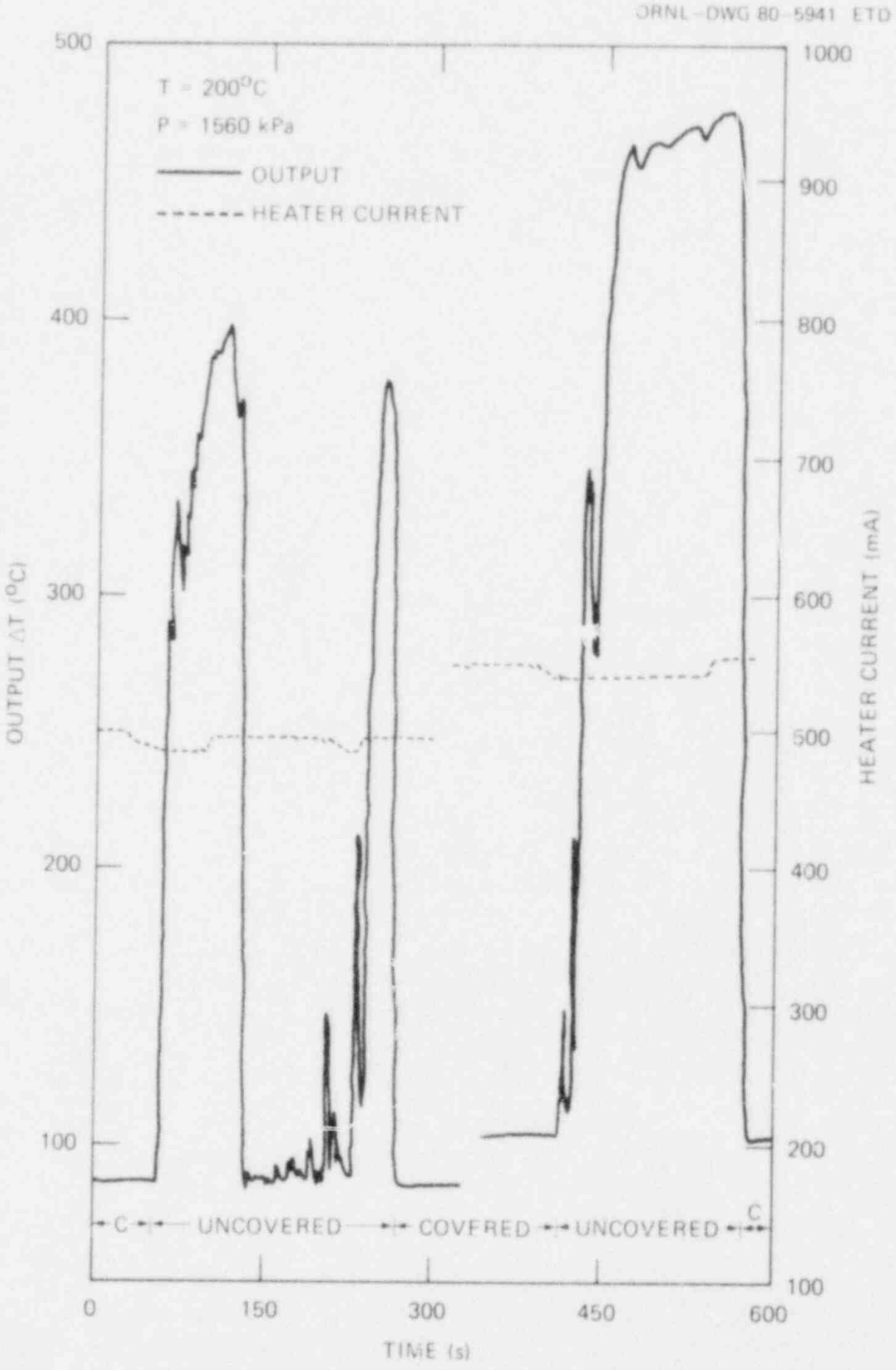

Fig. 4. Navy-type HTC output recorded vs time during natural convection tests at 200°C. Heater current ranged from ~500 to ~550 mA. During period denoted as covered, active part of probe was immersed in saturated liquid. During uncovered period, probe was immersed in saturated steam.

pressure and temperature were 1.6 MPa and ~200°C, respectively. The temperature decrease from 400 to ~90°C with subsequent reheating to ~375°C is believed to be caused by a period of rewetting of the probe's heated region by condensate. The upper part of the TITF pressurizer was not heated during these tests and condensation on internal surfaces probably did occur. Subsequent tests with the Navy probe oriented vertically in the transparent countercurrent steam-water test facility showed that this type of rewet behavior did indeed occur with a vertically oriented probe.

If a probe of this type is to reliably indicate degraded cooling conditions or the presence of a high void fraction environment, some provision should be made to protect the probe's heated region from droplets and condensate in the flow stream that may be de-entrained on surfaces above the probe.

2.1.3 Commercial heated RTD

A thermal-type liquid level/interface monitor with resistive thermometers monitored differentially was installed in the TITF pressurizer and tested under high temperature and pressure conditions. The device used was purchased from Fluid Components, Inc., Canoga Park, California, as Model FR-77LL-HT. The sensor head (Fig. 5) consists of two pairs of cylinders, connected on one end to the probe body and on the other end by a support bar. One pair of cylinders contains a heating element and an RTD that is in good thermal contact with the heater. Separated by a short distance from the heated assembly the other pair contains an RTD that is used as a temperature reference.

The sensor was installed horizontally along a radius of the pressure vessel (Fig. 1). The sensor head was positioned ~3 cm from the vessel centerline; the plane of the sensor elements was horizontal. The vendor-supplied control unit was used to provide a constant power level of ~2 W to the probe heater.

Tests were conducted with the heated RTD at saturated conditions covering from 100 to 300°C (212 to 572°F) with pressures from 100 to 820 kPa (15 to 1190 psia). When the probe was immersed in saturated liquid, its output was always <10 mV. Steady-state output voltages obtained when the probe was in saturated steam are plotted vs system pressure in Fig. 6. The decrease of the output ΔT with increasing pressure reflects the increase in natural convection heat transfer coefficient with increasing pressure.

Unsteady output temperatures were again observed with the heated RTD when the sensor head was in saturated steam. The effects were most pronounced at the highest pressures, for example, the output signals at 300°C shown in Fig. 7(a). The exact mechanism for these effects is not understood. However, at the recommendation of the probe manufacturer, a half cylinder was added to the sensor head, forming a cover for water drops that might fall down on the sensor. Results obtained after this modification were greatly improved [Fig. 7(b)], suggesting that falling drops were affecting the probe output.

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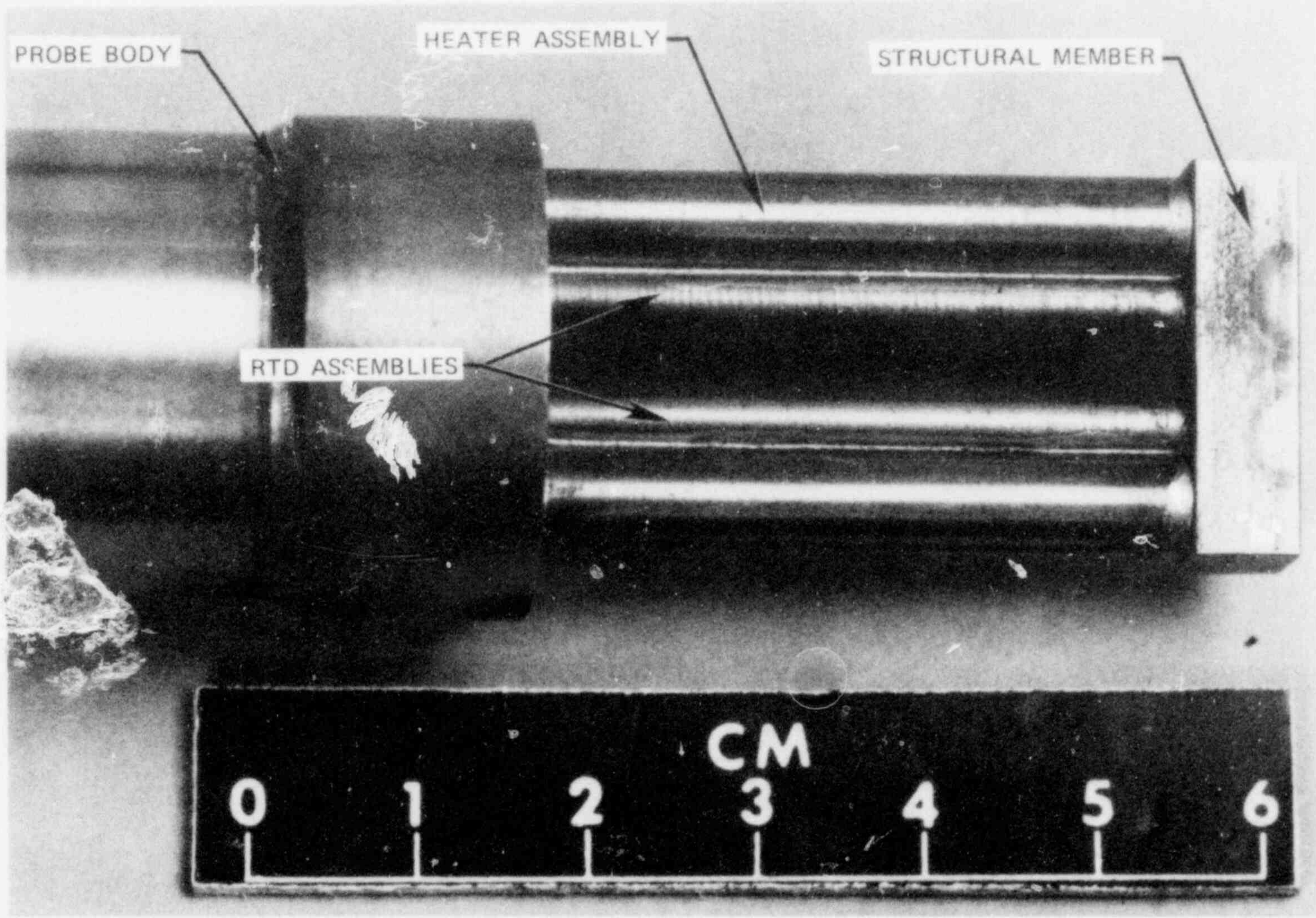

Fig. 5. Sensor head of commercial heated RTD device tested in high-pressure natural convection. Device was installed for testing as in plan view shown.

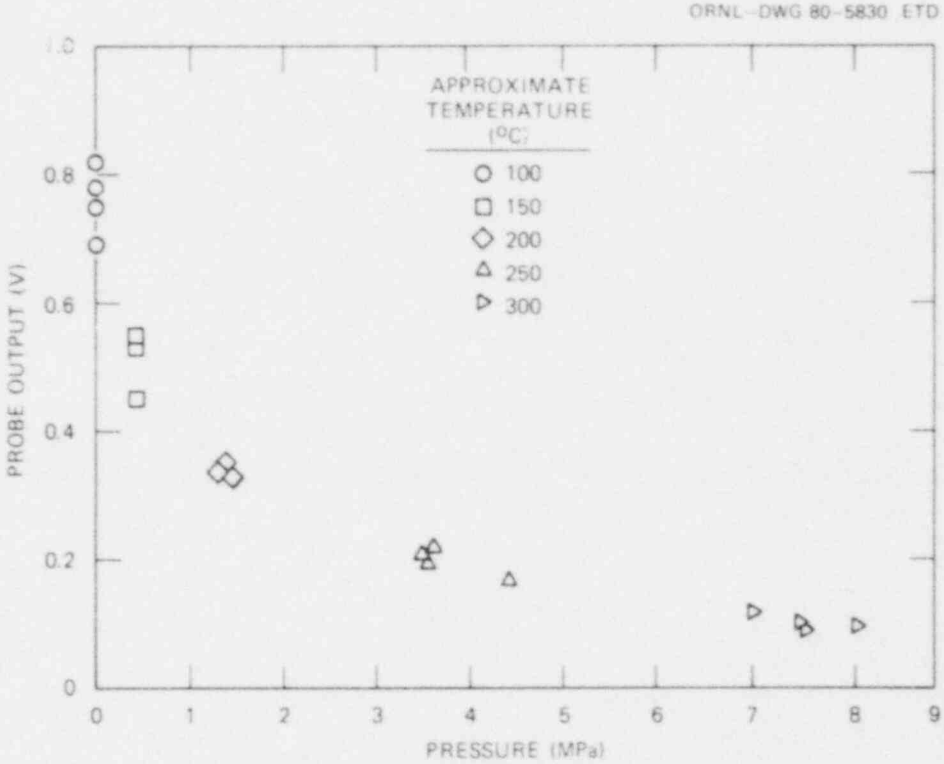

Fig. 6. Steady-state output, obtained from heated RTD device when sensor head was immersed in saturated steam, plotted vs system pressure.

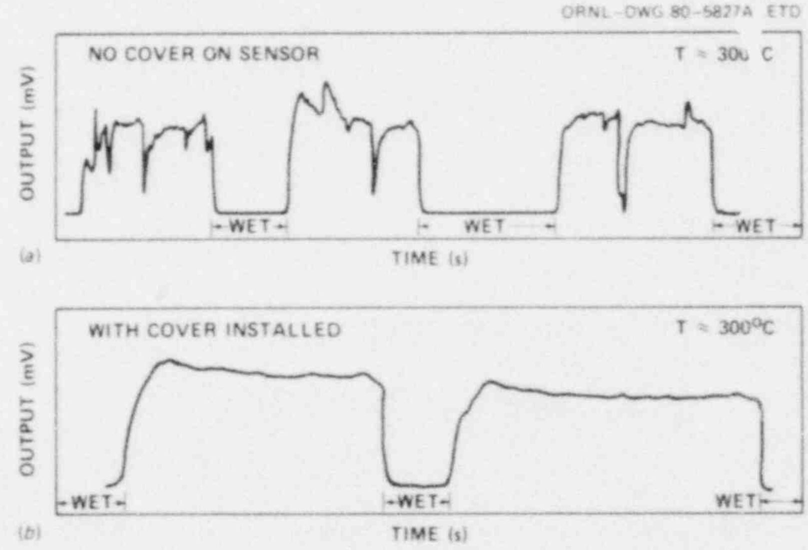

Fig. 7. Time-dependent output obtained from heated RTD device during natural convection experiments performed at ~300°C (pressure ≈8.6 MPa). (a) Data obtained with bare sensor head shown in Fig. 5, (b) data obtained while sensor head covered as described in text.

2.2 Forced Convection Tests

Experiments to evaluate the performance of thermal-type coolant sensors under forced convection conditions were performed in a low-pressure countercurrent steam-water test facility (Fig. 8) and in the Advanced Instruments for Reflood Studies (AIRS) Test Stand.

2.2.1 Countercurrent loop tests

The test section of the countercurrent facility is constructed of 10-cm-ID polysulfone (TM) piping. A 20-mm-thick perforated plate (the tie plate) with 10.5-mm-diam holes on a 14.5-mm^2 pitch was installed (Fig. 8).

During testing, subcooled water enters the test section from above, while steam flows from below. Flow rates of steam and water may be used to produce variable-density froths and droplet flow regimes in the region above the tie plate. Tests performed in the low-pressure countercurrent facility are useful in characterizing thermal probe output behavior, while simultaneously observing the steam-water flow regime through transparent test section walls.

During this period, the Navy-type HTC and the probe designated ORNL I were tested in the countercurrent loop. The ORNL probe was installed horizontally ~2 cm above the tie plate. The Navy probe was vertically oriented with the heater ~25 cm above the tie plate. Data obtained with both probes in single-phase liquid flow and single-phase steam were generally like those obtained in natural convection tests: the ΔTs obtained in steam flow were much greater than those in liquid flow.

In two-phase flow, the output ΔTs for both ORNL and Navy probes remained virtually identical to the values observed when the flow was single-phase liquid. This effect held true even when visual observations revealed that relatively little of the liquid phase was present near the probe. (No in situ void fraction measurements were made during these tests.) The fact that neither of the probes tested had any type of droplet or splash shield attached during these experiments should be emphasized.

2.2.2 AIRS Test Stand tests

The AIRS Test Stand[6] (Fig. 9) is a once-through cocurrent steam-water flow system designed for pressures up to ~830 kPa (120 psi). The HTC probe ORNL II, described in the previous report,[3] was installed without any splash shield in a horizontal orientation at the location shown in Fig. 9. A triple-beam gamma attenuation densitometer provided chordal average void information 80 cm below the test probe. A full-flow turbine meter gave an indication of the pipe average velocity in two-phase flow.

Tests were performed at system pressures of 380, 520, and 725 kPa (55, 75, and 105 psia). Data plotted in Fig. 10 show the output ΔT as a function of measured void fraction and heater power. Data suggest that the variation of void fraction and velocity at a given pressure had little influence on probe output. When the flow consisted of only saturated or

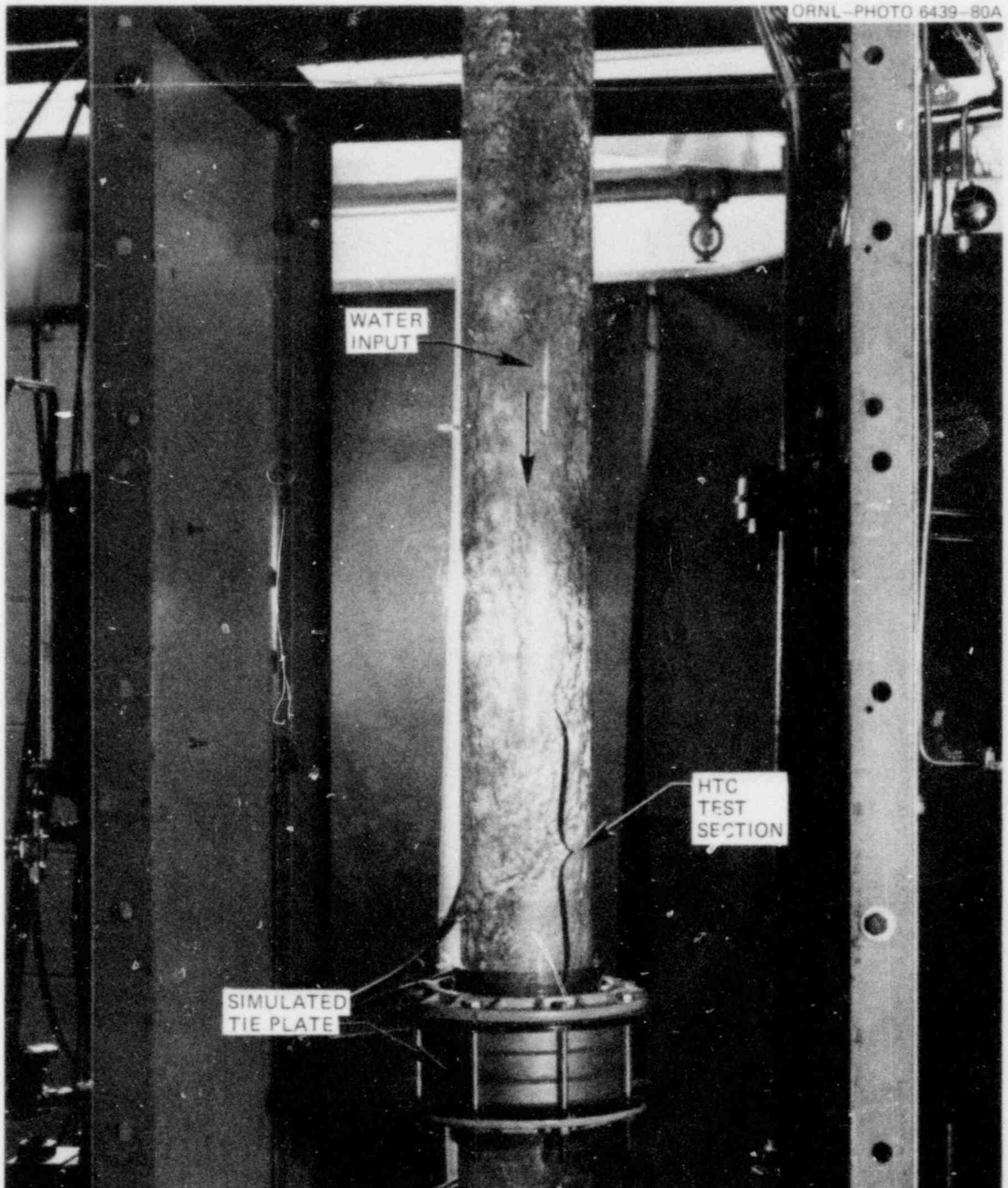

Fig. 8. Low-pressure countercurrent test facility used for observing steam-water, two-phase flow regimes during testing of thermal coolant sensors.

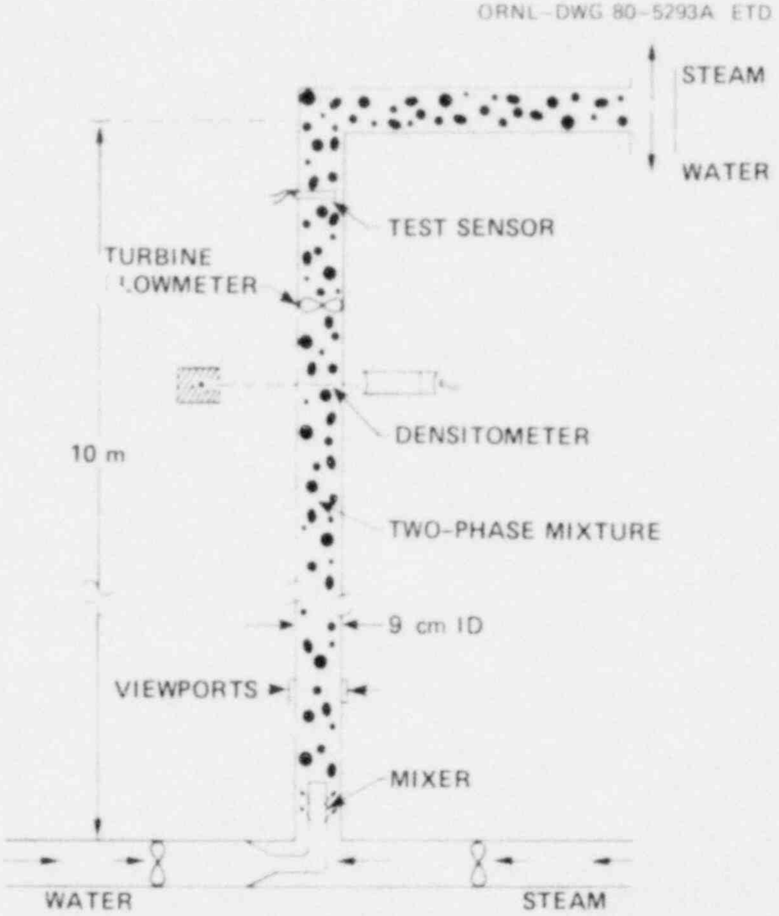

Fig. 9. Forced convection steam-water test facility (AIRS Test Stand) used for thermal sensor evaluation at low and moderate pressures.

superheated steam (no liquid phase), the probe output increased significantly.

Heater powers used in these tests resulted in probe surface heat fluxes of $\lesssim$9.10 W/cm^2 (58.7 W/in.^{2}). This figure is ~70% of the maximum decay heat surface heat flux from a typical nuclear fuel rod and ~5% of the maximum full power surface heat flux expected from such a pin.

The tests performed in these two forced convection facilities clearly indicate that only a minimal amount of liquid is required to cool a thermal sensor operating at decay heat power rates to relatively low ΔT outputs. If such bare probes are to be used to detect the approach to inadequate cooling conditions (particularly if they are to work in forced convection high-void-fraction flow), some means must be developed to reliably isolate the sensors from the liquid-phase present in the flow stream. Current experimental work is addressing that need.

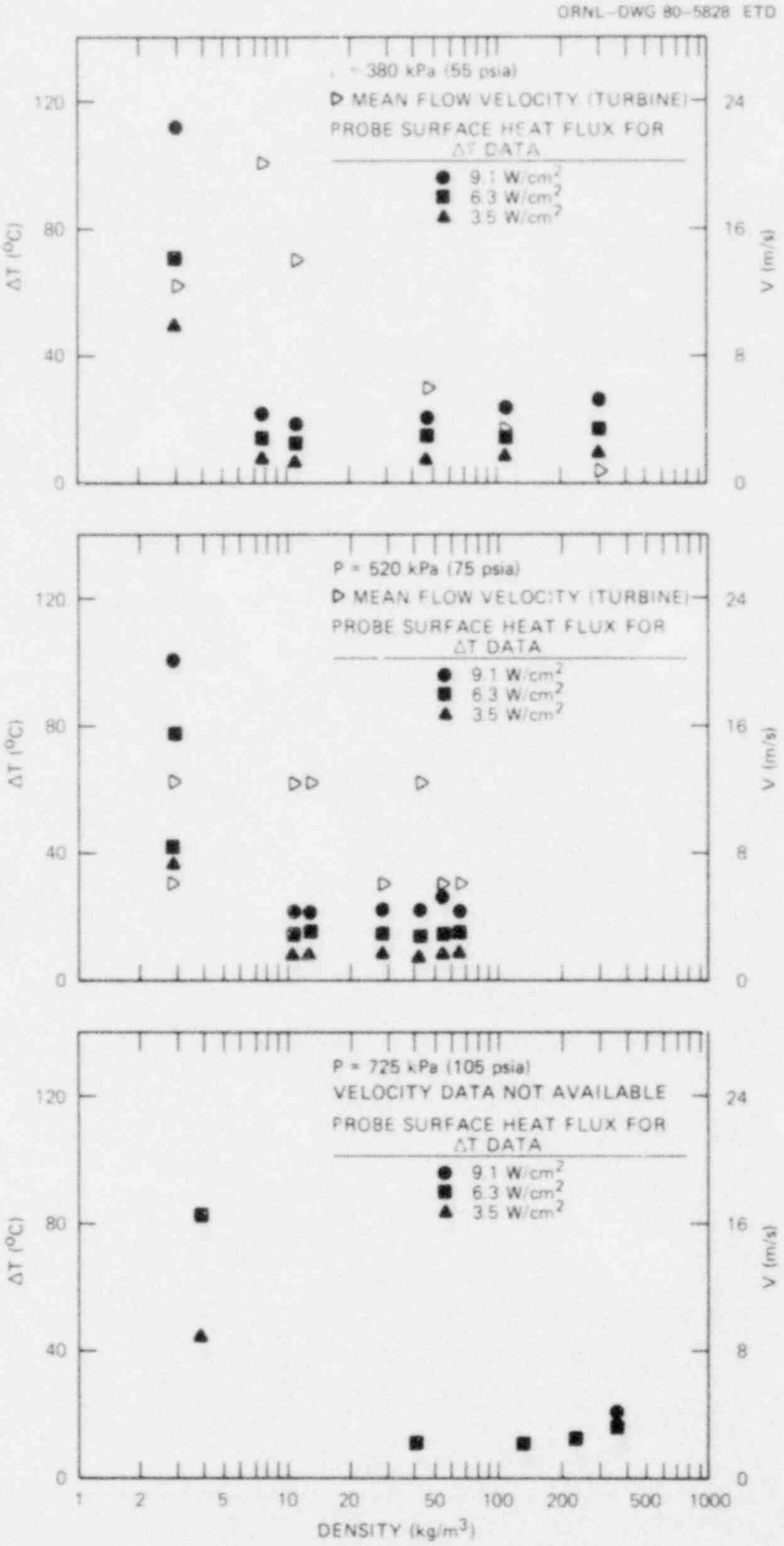

Fig. 10. Temperature difference data obtained at 380, 520, and 725 kPa with HTC sensor ORNL II in forced convection in AIRS Test Stand. Data are plotted vs density derived from densitometer readings. Flow velocities indicated by turbine and heater power are parameters.

3. ACOUSTIC LIQUID LEVEL PROBE DEVELOPMENT

The acoustic techniques of level detection being considered use the effects of the density of the surrounding medium on the propagation times of torsional waves in a ribbon-type waveguide. The principles involved in this technique and potential advantages of the method were covered in the previous quarterly report[3]; this research has shown that the effects of temperature on propagation speeds of torsional and extensional waves in a waveguide of 1- by 2-mm cross section may be considered to be linear over a temperature range from 0 to 70°C. Information from extensional waves was used successfully to correct the propagation times of torsional waves in a prototype sensor, yielding more accurate measurements of liquid level in a room temperature facility.

During this period, the same sensor was used to show that propagation times of torsional signals are affected by the presence of voids in the surrounding medium. The 225-cm-long waveguide was immersed in water, and air was bubbled up through the facility. The approximate mean void fraction in the tank at any given time was deduced from the amount of swell in the water level at the top of the tank. Figure 11 shows data obtained for the total propagation time of torsional waves along the waveguide as a function of the estimated void fraction in the tank. Propagation time of a torsional wave along the waveguide when it was completely dry was used to determine the theoretical propagation time (903.2 μs) shown at 15% void. Actual data exceed the predicted curve somewhat, but the variation with void fraction is approximately linear with the correct slope.

An ultrasonic sensor (Fig. 12) suitable for installation in the TITF pressurizer was received from Panametrics, Inc., Waltham, Massachusetts.

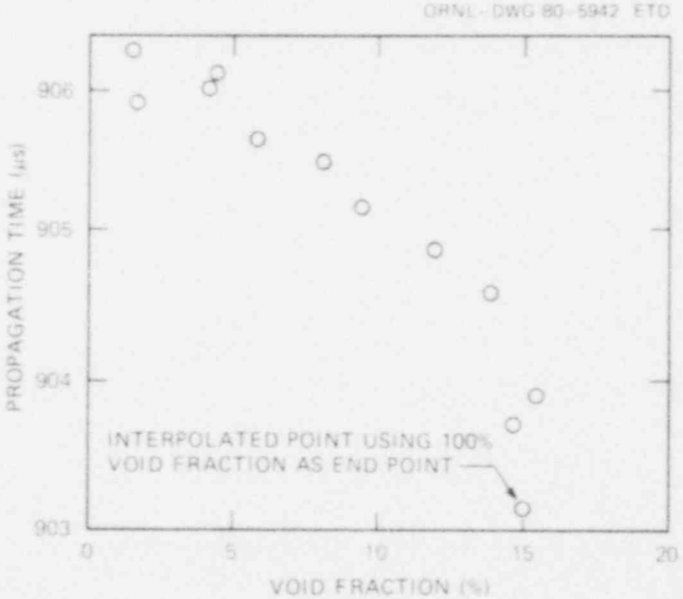

Fig. 11. Propagation time (μs), measured for torsional waves along a ribbon-type waveguide, plotted vs mean void fraction in vessel of room temperature level test facility.

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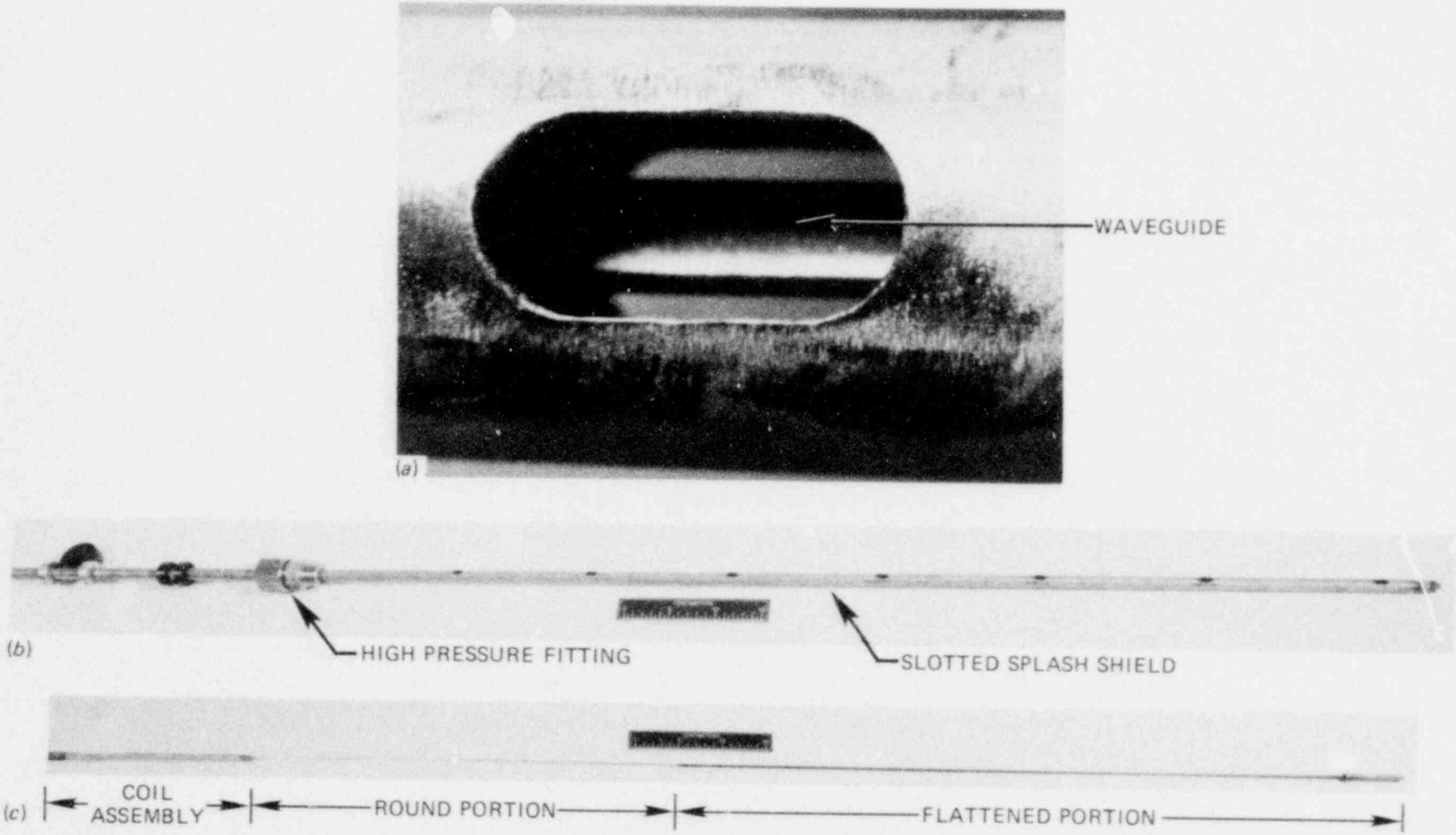

Fig. 12. Photograph of active portion of dual-mode torsional-extensional level sensor to be tested at high-temperature and pressure. (a) Close-up of 1- by 2-mm stainless steel waveguide viewed through slot in splash shield, (b) outer cover of probe and fitting, and (c) probe internals.

Separate coils are used in the transducer to produce torsional and extensional waves in the waveguide. The active length of the level sensor ribbon is about 76 cm. A somewhat longer piece of round stainless steel wire is attached to the magnetostrictive rod above the transducer so that echos from the upper end of the sensor assembly are delayed and return to the transducer after the reflections of interest. The sensor ribbon is contained inside a perforated stainless steel pipe. The whole assembly is to be sealed into the TITF pressurizer just below the transducer section. Actuating and signal leads are brought out a hermetic, high-pressure seal at the top of the probe assembly.

Initial tests were performed with the sensor in the room temperature level test facility. The sensor operated correctly under these conditions. Efforts are under way to complete installation of the probe in the TITF. A five-point TC rake was fabricated to determine the vertical temperature gradient in the pressurizer when the ultrasonic device is tested. A digital data processing oscilloscope was received and will be used to process time delay information from the ultrasonic level device.

4. CONTACTS WITH REACTOR VENDORS

On April 2, 8, and 9, 1980, four members of the ATPI Program staff met with representatives of the three U.S. PWR vendors (Babcock and Wilcox, Westinghouse, and Combustion Engineering) at their facilities to discuss proposed PWR reactor vessel water level monitoring systems (RVLMS). A staff member from the U.S. NRC, Division of Reactor Safety Research, also participated in the meetings. The liquid level sensor concepts being considered at ORNL were discussed, and the proposed test program was outlined. An important goal of the meetings was to solicit comments from the vendors on the suitability and installation requirements for power reactor use of level sensors like those under development at ORNL.

Significant comments made by the vendors regarding level detector development include the following:

1. Both the thermal and acoustic means of level detection being investigated at ORNL are potentially useful as PWR instrumentation.
2. Additional proof-of-principle testing is required for both methods before either is ready for application as a coolant sensor in a PWR. These tests are an appropriate area of work for ORNL.
3. Differential-type HTCs appear to require relatively little development for use as an RVLMS, but they may not be very useful during normal reactor operation.
4. Ultrasonic waveguide level sensors will require a significant development effort for use as an RVLMS, but they are a potentially useful instrument during both normal and off-normal operation.
5. Testing of thermal sensors should encompass high pressures [$\lesssim$15.5 MPa (2250 psia)] and high flow velocities [20 m/s (~60 ft/s)] and should consider the effect of liquid fall-back (de-entrainment) on sensor output.
6. The ultrasonic sensor's operation should be verified under known two-phase flow conditions, and the sensor's durability with high flow velocities should be verified.
7. Qualification of proposed level devices to Class 1E (safety grade) specifications should occur <u>after</u> proof-of-principle testing. These qualification tests are a reactor vendor responsibility.

Subsequently, a trip report covering all three vendor visits was prepared.[7] The report included descriptions of the vendors' particular approaches for meeting the NRC's recent inadequate core cooling requirements. At the time of the April 1980 meetings, these were the vendors' intentions:

1. Westinghouse was developing a level measurement system based on pressure difference measurements from top to bottom of the reactor vessel and from the top of the reactor vessel to the hot leg evaluation.
2. Combustion Engineering was pursuing analytical studies to determine the measurements that might be required to detect degraded cooling conditions in the reactor vessel. After evaluating several RVLMS concepts, Combustion Engineering now feels that an array of HTCs is the most promising for near term implementation.

3. Babcock and Wilcox has completed studies that, in their opinion, demonstrate that maximum fuel clad temperature may be conservatively determined using information from the core exit fluid TCs and the system pressure. They therefore believe that no additional in-vessel instrumentation is necessary for Babcock and Wilcox plants to meet the requirement of the inadequate core cooling guidelines.

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