CONF-901109--1

CONF-901109--1

DE90 008748

MEASUREMENT OF TWO-PHASE FLOW MOMENTUM WITH FORCE TRANSDUCERS*

J. E. Hardy
Instrumentation and Controls Division

J. E. Smith
Engineering Technology Division

Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

Two strain-gage-based drag transducers were developed to measure two-phase flow in simulated pressurized water reactor (PWR) test facilities. One transducer, a drag body (DB), was designed to measure the bidirectional average momentum flux passing through an end box. The second drag sensor, a break through detector (BTD), was designed to sense liquid downflow from the upper plenum to the core region.

After prototype sensors passed numerous acceptance tests, transducers were fabricated and installed in two experimental test facilities, one in Japan and one in West Germany. High-quality data were extracted from both the DBs and BTDs for a variety of loss-of-coolant accident (LOCA) scenarios. The information collected from these sensors has added to the understanding of the thermohydraulic phenomena that occur during the refill/reflood stage of a LOCA in a PWR.

NOMENCLATURE

A = cross-sectional area of drag transducer
F = drag transducer force output
g = acceleration of gravity
M = mass flow rate measured by drag sensor and turbine meter
p = pressure
V = velocity
α = void fraction
ρ = density

Subscripts
c = gravitational constant
dt = drag transducer
g = gas phase
l = liquid phase
t = turbine meter

INTRODUCTION

A joint program to study three-dimensional thermohydraulic phenomena in the vessel of a PWR during the refill/reflood stage of a LOCA was initiated by the U.S. Nuclear Regulatory Commission in cooperation with its counterparts in West Germany and Japan (1). The principal experimental facilities in the International 2D/3D Refill/Reflood Experimental and Analytical Research Program were the Slab Core Test Facility (SCTF) in Japan and the Upper Plenum Test Facility (UPTF) in Germany (2,3). SCTF simulated the core region of a PWR whereas UPTF was a full-scale model of an upper plenum. Coupling the results obtained at these two principal facilities was a major problem. The flows at the interface boundary (the end box/upper-core support plate region) of the two test vessels were measured and matched as closely as possible. The role of the Oak Ridge National Laboratory (ORNL) was to develop instrumentation to measure the flows at the core/upper plenum interface.

The instrumentation systems devised were strain-gage-based transducers developed using innovative and previously untried techniques (4). These techniques were necessary because of the stringent design criteria. The sensors were required to be sensitive over a very wide range of flow rates and to survive the hostile steam/water environment. Additionally, the DBs were required to cause minimal flow disturbances. The transducers also had to have a high resonant frequency, have a high endurance to cyclic loading (fatigue), and exhibit minimum inaccuracies due to thermal effects.

The DBs employed a unique full-bridge, strain gage configuration to measure the force induced by the passing fluid. With a constant drag coefficient, the force on the DB is proportional to the average momentum flux for the sampled region. This principle was used in the BTD design also. Parts of the end box were utilized to house the transducer and to be the drag target. The use of existing vessel internal hardware resulted in minimal effects on the flow. The full-bridge configuration allowed for a highly sensitive transducer with a 1000 to 1 range. High-temperature strain gages were matched to each other and to the physical

---

* Research sponsored by the U.S. Nuclear Regulatory Commission and performed at the Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under Contract No. DE-AC05-84OR21400.

properties of the transducer material to optimize temperature compensation and minimize thermal uncertainties. The DB sensors were designed robustly to withstand thermal and mechanical shocks while still having a high resonant frequency of ~70 Hz.

The BTD design was similar to that of the DB in that it was a strain gage transducer that responded to fluid momentum forces. The specific idea was to place a drag target under tie-plate flow holes to detect water passing down through the flow holes. A full-bridge configuration was employed to meet sensitivity and rangeability requirements. The BTD was allowed to disturb the flow in the end box. The BTD was designed to withstand the expected severe thermal and mechanical shocks and have a high resonant frequency of 48 Hz.

The drag transducer designs passed all acceptance tests including system accuracy, sensitivity, stability, and survivability. In use in the major test facilities, the sensors produced high-quality data. In some DBs in UPTF, fatigue failure of individual strain gages occurred. Minor design modifications were undertaken to alleviate this problem.

DRAG TRANSDUCER DESIGN

The basic designs of the drag transducers were driven by the stringent design criteria (5,6). The major constraints on the two designs were the environmental conditions and the system geometry. The test facilities contained steam/water mixtures with pressures to 2.1 MPa and temperatures to 300°C. Many of the experiments involved steam and subcooled water that resulted in large, fully reversed multicycled loads. These condensation shocks produced forces that were as much as an order of magnitude larger than the full-scale rating of the drag transducer. In addition, thermal transients on the order of 40°C/s were possible. The DB was to cause minimal flow disturbance, whereas local flow disturbances were acceptable with the BTDs. Both sensors had to fit in the complicated geometry in and around the end box and upper-core support plate.

Drag Body

The DB was to measure the vertical two-phase momentum flux passing through the end box in either direction. The force measurement range for the drag body was 0.9 to 220 N with a resolution of 1000 to 1 or 0.1% of full scale (FS). The allowable uncertainty for the entire measurement system was to be less than ±5% FS, which included thermal and transient condition effects. Because some two-phase flow phenomena occur at relatively high frequency, the drag transducer was required to have a high resonant frequency.

A full bridge (four active strain gages) was selected to measure the strain on the tie plate through a transducer core. The strain, through actual flow calibrations, was related to force. The full-bridge configuration allowed for compensation of temperature effects on the gages (apparent strain), for additive gage signals to increase output strength, and for negating nonaxial loads and asymmetrical moment loadings. More specifically, the gages were mounted in such a way that two gages were in tension and two were in compression. This caused the gage outputs to be additive in the bridge circuit and helped increase the signal-to-noise ratio. Matched-temperature-response gage pairs were hand-selected and put in adjacent legs of the bridge to reduce temperature effects in the transducer. In addition, two type-K thermocouples were attached to the transducer core to give an indication of the strain gage temperature and to allow for additional thermal-induced strain corrections. The thermocouples consisted of the same materials as the strain gages and were fabricated by the same methods to create similar temperature responses.

The strain gages were a high-temperature-weldable type made of a looped nichrome wire to give a 350-Ω resistance. The nichrome wire was surrounded by an insulating powder of magnesium oxide (MgO) and was finally encapsulated in Inconel 600. The strain gages were swaged down to their final size and then seal welded. The gages as well as the type-K thermocouples were spot welded to the transducer core. The transducer core (Fig. 1) consisted of an elongated proving ring, an overload protective stop, and a support structure and tie-down piece. The elongated ring allowed for sufficient flat surfaces to spot weld the gages and thermocouples. The overload stop prevented the strain gages from being loaded beyond their limit, especially during condensation shocks. The transducer core was made from Inconel X-750. The steps for building a drag body transducer are shown in Fig. 2.

The assembled transducer was located in an end box as shown in Fig. 3. The sensor was placed inside a support tube and did not perturb the local flow conditions. For the transducer to measure only the flow force on the tie plate, a portion of the tie plate had to be freed from the end box and be supported only through the transducer core. The tie plate had a slot cut through it in an octagonal pattern (Fig. 4). Some of the end box supports also were cut to ensure that the tie plate cutout was free floating, supported only by the transducer core.

The lead wires from the sensor traveled through the vessel interior and then to the control room, a total distance of 80 m. The resistance in these wires varied enough (because of temperature transients) to significantly affect the transducer output. To reduce this effect, a six-wire system was employed that allows the bridge excitation voltage to be sensed and controlled at the strain-gage bridge completion location. This negates the effect of the lead wire resistance changes.

Breakthrough Detector

The BTD was to measure the fluid momentum passing down through the tie-plate flow holes. A drag target was located under three flow holes of the end box. If the measured fluid momentum was greater than a predetermined value, breakthrough was said to have occurred. Breakthrough is further defined as a downward flow of liquid from the upper plenum to the core. The force measurement range for the BTD was 0.0 to 2.0 N with a resolution of ±0.02 N. The allowable uncertainty for the entire measurement system was to be less than ±10% FS, which included thermal and transient condition effects. The BTD was also required to have a high resonant frequency.

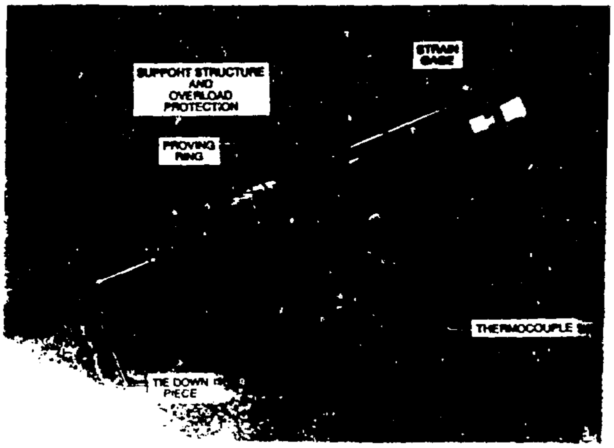

Fig. 1. Drag body transducer core.

Fig. 2. Genesis of a drag body transducer.

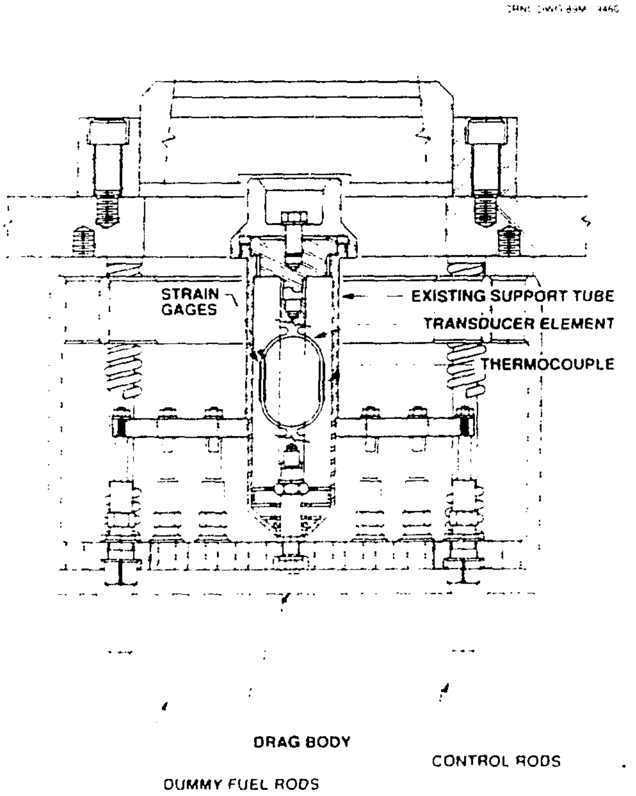

Fig. 3. Drag body transducer location relative to end box components.

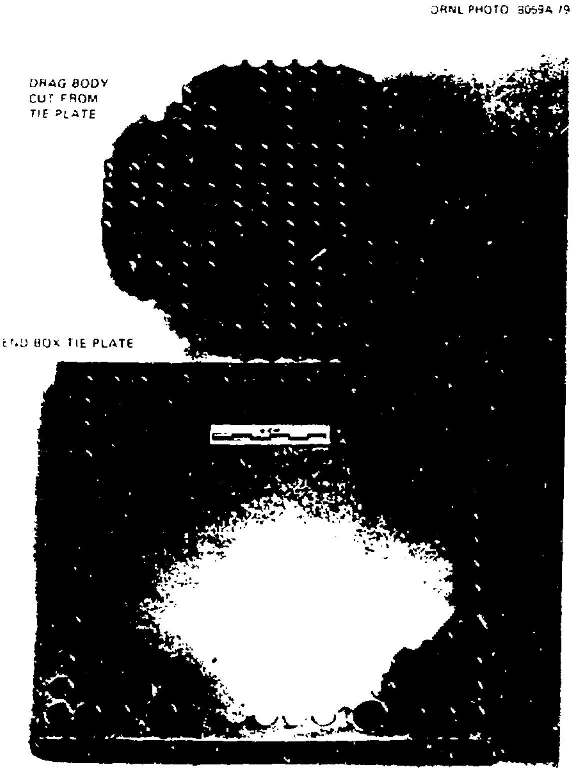

Fig. 4. Cutout pattern of tie plate drag body target.

The basic design was that of a cantilever beam fixed to the bottom of the tie plate with circular targets at the end of the beam (Fig. 5). Because the BTD was required to measure only water downflow and because of its near proximity to the tie plate, the frame housing around the cantilever beam was designed as a mechanical stop in the upward direction. The BTD may deflect only a small amount upward, which prevents the targets of the BTD from touching the tie plate and blocking the flow.

The BTD assembly was made of 304 stainless steel. The cantilever beam and targets were made of 17-4 PH stainless steel. Because the BTD is used as a detector or limit switch for breakthrough, the sensitivity of the sensor is not as critical as in the DB. To this end only two active strain gages were used in conjunction with two dummy gages to complete the full bridge. The dummy gages were used to compensate for thermal effects. A type-K thermocouple was installed with the gages to aid in compensating for apparent strain effects.

The lead wires from the BTD were routed through the vessel interior and then to the control room, similar to the DBs. A six-wire signal conditioning system was used to negate the effect of the lead wire resistance changes.

DESIGN ACCEPTANCE TESTING

Along with the qualifying tests to verify that the drag transducers met the design criteria, several areas of concern were specifically addressed (7). These areas were signal-to-noise ratio, dynamic response and loading, rangeability, and the effects of varying temperature. As noted in the design section, attempts were made to mitigate these concerns. Testing was required to evaluate the effectiveness of the design solutions. Prototype drag transducers were subjected to thermal shocks, dynamic analysis, mechanical life tests, abnormal loading effects, and service testing.

Each individual strain gage was hydrostatically tested by the manufacturer at 17.2 MPa and 260°C. A prototype DB transducer was tested through more than one million full reversal cycles with no indication of fatigue damage. To evaluate sensor stability (zero shifts), drag transducers were subjected to 60 thermal shocks from 220°C to 25°C. Also, 100,000 load cycles were applied ranging from 25 to 100% rated load. There was no significant shift in zero for either of these tests. Drag transducers were tested at various temperatures under no-load conditions. The measured output is the apparent strain produced by thermal effects. For DBs the average thermal output was only ±0.02 N/°C. This translated to an in situ static calibration uncertainty for thermal effects of ±0.1% FS. For BTDs the average thermal output was ±0.04 N/°C. This translated to an in situ static calibration uncertainty for thermal effects of ±2.0% FS.

The resonant frequency of the cutout DB and BTD was determined by ringing the transducer and passing the output from a sensor to a Fourier analyzer to obtain the power spectral density as a function of frequency. The average resonant frequencies were −70 Hz from a DB and 48 Hz from a BTD, which were both well above the maximum desired frequency of 30 Hz (8).

The DBs and BTDs were calibrated with dead weights and by a universal testing machine that could apply purely axial loads. Resolution, hysteresis, nonlinearity, and repeatability were measured. The results for DBs indicated a resolution of 0.1% FS and a combined effect of hysteresis, nonlinearity, and repeatability of less than ±0.2% FS. The BTD test results showed a resolution of 1% FS and a combined effect of hysteresis, nonlinearity, and repeatability of less than ±2% FS. The DB was also calibrated for various asymmetric loadings. The effect of asymmetrical loadings was ±1% of reading.

Tests were also conducted to evaluate the effectiveness of the signal-conditioning electronics to reduce lead wire effects and to

ORNL-DWG 90M-5953

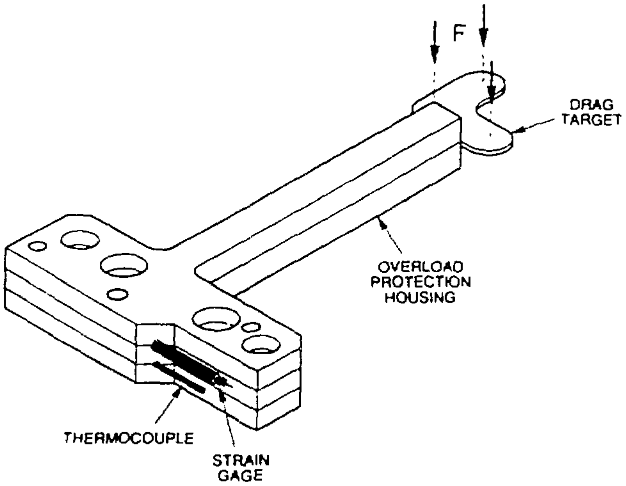

Fig. 5. Breakthrough detector schematic diagram.

ORNL-DWG 89M 19464

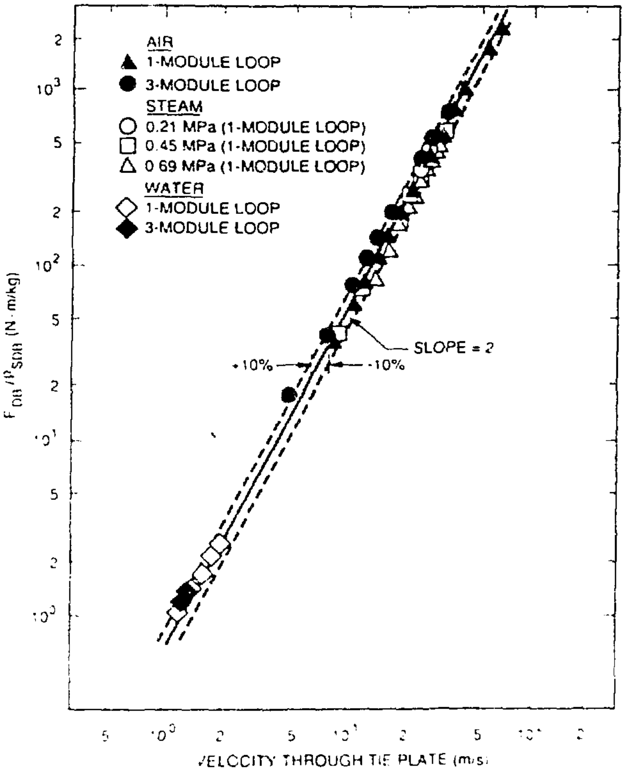

Fig. 6. Relationship between drag body measurements and velocity through the tie plate with compensation for fluid density (8).

determine the stability and accuracy of the electronics. Test results showed the combined inaccuracies from the signal conditioning to be less than ±1% FS.

Actual flow calibration was accomplished in single-phase water, steam, and air. The data from the calibration experiments are shown in Fig. 6 for DBs. The data show the relationship between the single-phase velocity through the tie plate (calculated from measured input flows and the tie-plate flow area) and the term $F_{dt}/\rho A_{dt}$. The agreement of the data with a line of slope 2 is quite good despite the wide range of conditions covered. The results also indicate that the DB output is proportional to the average fluid momentum (velocity squared) and that the DB has a constant drag coefficient for the range tested.

Because the BTD detects only water downflow, evaluation of its performance could be accomplished with single-phase liquid testing. Two-phase flow tests were not necessary to describe the BTD's sensitivity, rangeability, and so forth. Data compiled from single-phase downflow experiments are shown in Fig. 7. The data exhibit very little scatter and fall on a line with a slope of 2. Once again the results indicate that the BTD output is proportional to the average fluid momentum being sampled by the detector.

To demonstrate functionality and survivability, DBs and BTDs were tested at ORNL under conditions that simulated flows expected in the foreign test facilities. Air/water and steam/water experiments were conducted with sensors over a 2-year period. All transducers survived the testing intact and produced data that met all design criteria.

ORNL-DWG 90M-5954

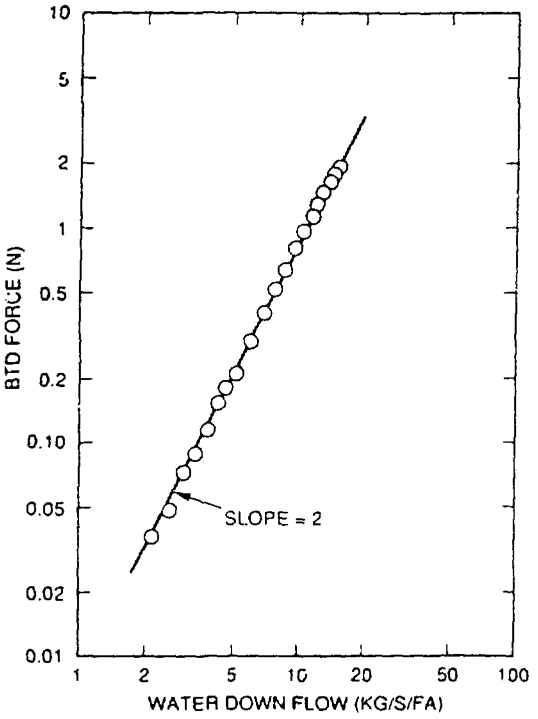

Fig. 7. Relationship between breakthrough detector measurements and water downflow rates.

EXPERIMENTAL RESULTS

To assist in evaluating the DB performance in two-phase flow, comparisons were made at ORNL with differential pressure measurements across the tie plate and with measured flow inputs converted to momentum flux. Previously described single-phase calibration tests indicated that the DB output was proportional to the average fluid momentum. By measuring the pressure drop across the tie plate, which should be likewise proportional to flow momentum, a check on the drag transducer performance can be made with a more conventional measurement technique.

A comparison of DB and tie-plate differential pressure (dP) measurements is exhibited in Fig. 8. The outputs of the two instruments are in agreement, as is evidenced by the data falling in a close band around a line with a slope of 1; thus, both are representative of the steam/water fluid momentum. The scatter of data at the low values on the figure is caused by the differential pressure measurement. The dP system lower range limit is close to 20 mm of water.

A second evaluation method is to compare the measured momentum flux by the DB to the momentum flux calculated from the input flow rates. For two-phase flow the momentum flux relation is

$$F_{db}/A_{db} = (\alpha\rho_g V_g^2/g_c) + (1 - \alpha)\,\rho_l V_l^2/g_c \ . \qquad (1)$$

Tests were conducted with a two-phase mixture of steam and water with both fluids flowing upward through the tie-plate region. The agreement between the momentum flux obtained from the DB and the measured inputs was not as good as in single-phase flow, but the general trend and internal consistency of the data indicate that the DB does measure a two-phase momentum flux. This comparison is shown in Fig. 9.

To effectively couple the Japanese and German test results, the mass flows at the tie plate must be matched. Thus, the required quantity is the mass flow rate across the tie-plate region and not the

ORNL-DWG 89M 19463

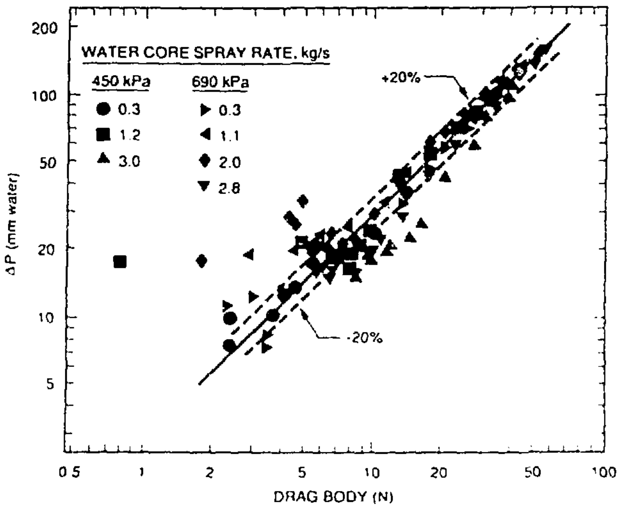

Fig. 8. Comparison of differential pressure and drag body measurements across the tie plate (8).

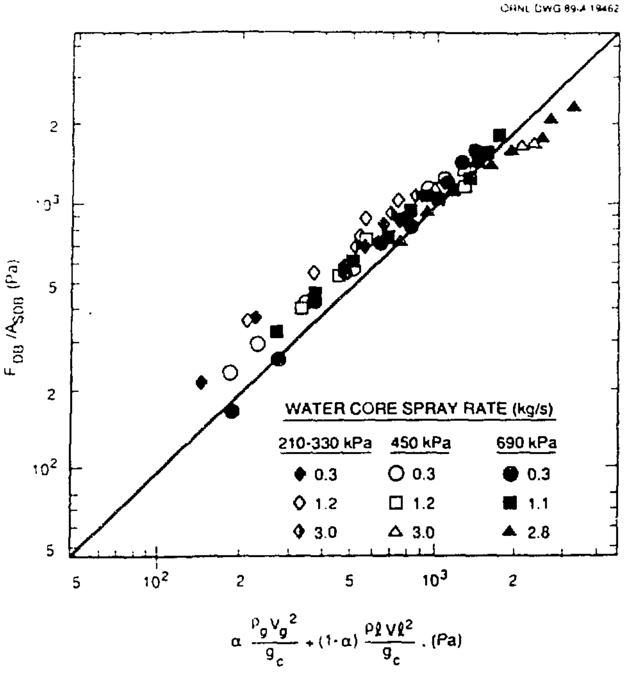

Fig. 9. Comparison of momentum flux measured by the drag body with momentum flux calculated from measured inputs (8).

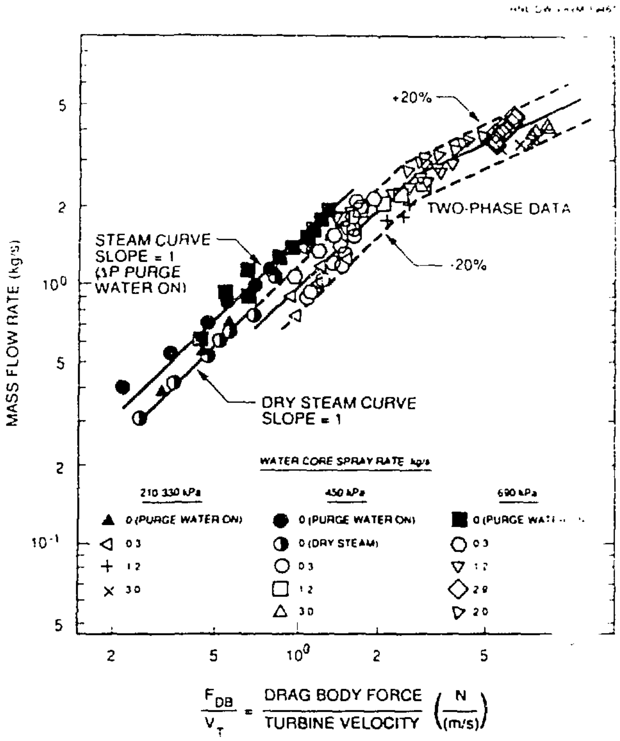

Fig. 10. Comparison of mass flow rate from measured inputs with a mass flow model combining drag body and turbine meter measurements (8).

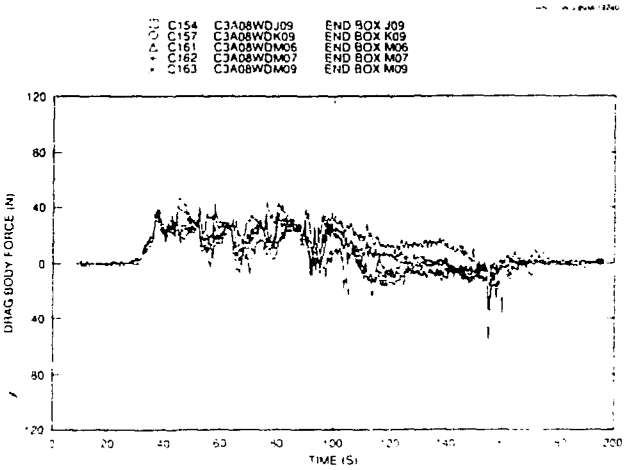

Fig. 11. Drag body measurements during countercurrent flow test (9).

fluid momentum. If the DB output is combined with other instrumentation, a mass flow rate may be calculated. These combinations were calculated and evaluated at ORNL but are beyond the scope of this paper (8). However, one of the combinations will be shown to illustrate the usefulness of the DB in measuring two-phase mass flow rates. Figure 10 contains data from a high-flow upflow test series that had steam velocities sufficiently high to carry all water injected into the core up through the tie plate and out the upper part of the vessel. Under these conditions the DB output can be combined with the output from a turbine meter to obtain a mass flow rate:

$$\dot{M} = F_{db}/V_t \ . \tag{2}$$

From inspection of the data in Fig. 10, it is evident that the combination of the two instruments provides a reasonable estimate of the mass flow across the tie plate. For two-phase flow the data scatter is small and the resulting correlation is single valued; that is, each DB/turbine point had a unique mass flow rate associated with it.

More than 50 major experiments and hundreds of minor tests were conducted at SCTF and UPTF over a 4-year period. DBs were installed in 4 locations at SCTF and in 36 locations in UPTF. Two BTDs were installed in SCTF while 94 were installed in UPTF. A variety of LOCA scenarios were simulated at different pressures and temperatures along with different emergency core-cooling methods. However, only selected data from testing at UPTF will be presented in this paper.

DB and turbine meters were installed in 36 of the 193 end boxes. In nine of the end boxes differential pressure measurements were made across the tie plate. Data from five DBs during a tie-plate countercurrent flow test are presented in Fig. 11. At ~30 s into the run all DBs showed upflow; however, at near 100 s three transducers switched to indicate downflow (J09, K09, and M09). A tie-plate differential pressure measurement across end box K09 exhibited a similar trend (Fig. 12). Turbine meters (Fig. 13) located in the same end boxes as the five DBs shown in Fig. 11 suggest the same trends. All velocities are positive until 100 s, when the data for end boxes J09, K09, and M09 switch to a negative value

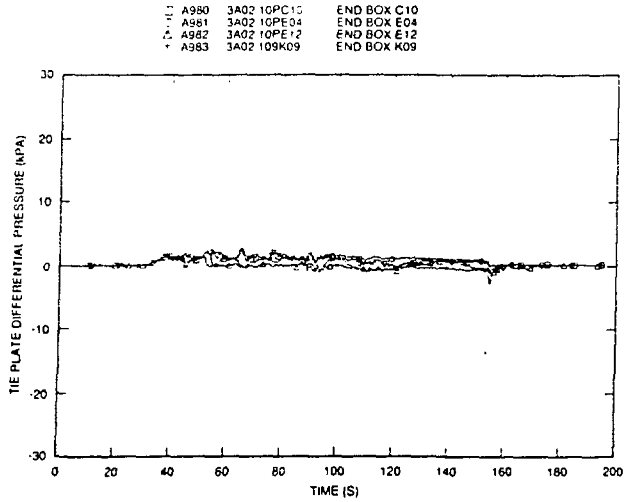

Fig. 12. Differential pressure measurements across the tie plate during countercurrent flow test (9).

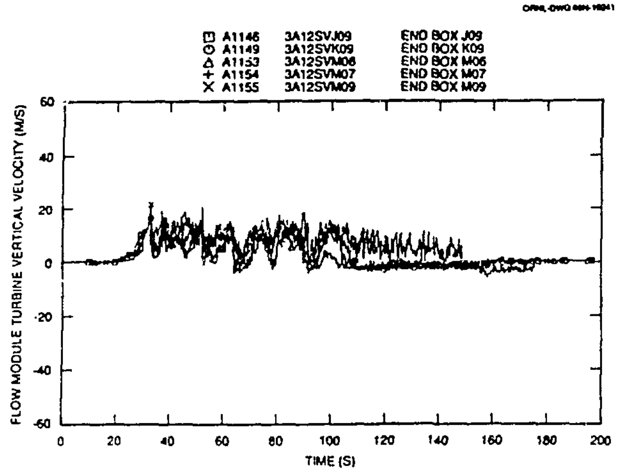

Fig. 13. Turbine meter measurements during countercurrent flow test (9).

indicating downward flow (Fig. 13). All three instrument types show a slow oscillatory flow behavior during the first 100 s of the experiment. This phenomenon is probably caused by U-tube pressure fluctuations in the vessel and downcomer.

Data from six BTDs are shown in Fig. 14. For the first 20 or 30 s of the test all BTDs indicated upflow. At ~45 s, large oscillations began with at least one BTD detecting breakthrough (a negative value). At 90 s, data from six BTDs showed significant breakthrough. This occurrence was verified by fluid temperatures, turbine meter velocities, and differential pressure measurements. The breakthrough phenomenon is highly dependent on local thermohydraulic conditions. At ~110 s, four of the BTDs indicated continuous breakthrough while two detectors continued to show upflow.

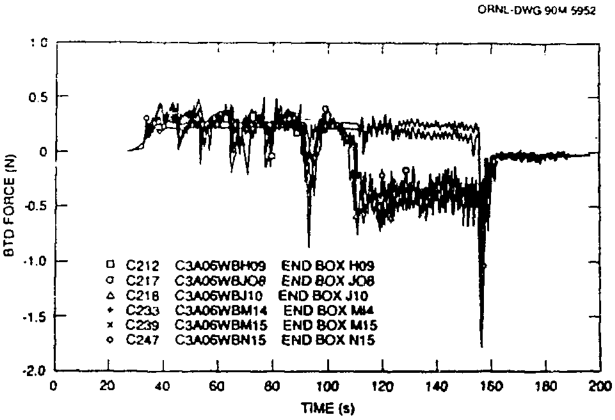

Fig. 14. Breakthrough detector measurements for countercurrent flow test (9).

Water and steam mass flow rates were calculated using a combination of instrument responses including the DBs and turbine meters. Algorithms were developed by the German participants in the 2D/3D program to determine the mass flow values; the particular algorithm employed depends on the flow regime present at the specific end box. Examples of the results of the algorithm calculations are presented in Fig. 15. As one might expect, the mass flow data for end boxes J09 and K09 indicate oscillatory upflow from 30 to 100 s into the run and a large water downflow beginning at ~110 s (Fig. 15a). The large amount of water present condensed all of the steam locally, as evidenced by the zero mass flow after 110 s (Fig. 15b).

SUMMARY OF RESULTS

Strain-gage-based drag transducers have been designed and fabricated to make two-phase flow measurements in simulated LOCA environments. The DB has a rangeability of over 200 to 1 with a resolution of 0.1% of FS. The overall measurement uncertainty during transient conditions is less than ±5% of reading. This uncertainty value includes thermal effects, gage factor variations, lead wire effects, signal-conditioning electronics errors, hysteresis, nonlinearity, and repeatability. The BTD has a resolution of 1.0% FS and an overall uncertainty of ±10% FS. For the DB the thermal effects, especially apparent strain, were reduced to acceptable limits by hand-selecting matched pairs of strain gages and employing them in a four-active-gage bridge arrangement. The four active gages also increased the transducer output, which raised the signal-to-noise ratio to a reasonable value. The BTD used two active strain gages and two dummy gages for temperature compensation, which resulted in sufficient accuracy for its detection requirement.

Rigorous acceptance testing results showed that the DB and BTD designs are capable of surviving the severe environment of high-temperature steam/water mixtures, the thermal shocks, and the mechanical shocks induced by condensation. With the exception of the high-cycle fatigue problem, the drag transducers functioned very well in the foreign experimental test facilities. The data produced were of high quality and aided substantially in understanding the two-phase flow phenomena that occur during the refill/reflood stages of LOCAs in PWRs. Mass flow rates were determined in the end box region of each foreign facility, thus allowing the two facilities to couple experiments in order to obtain overall vessel response to accident scenarios.

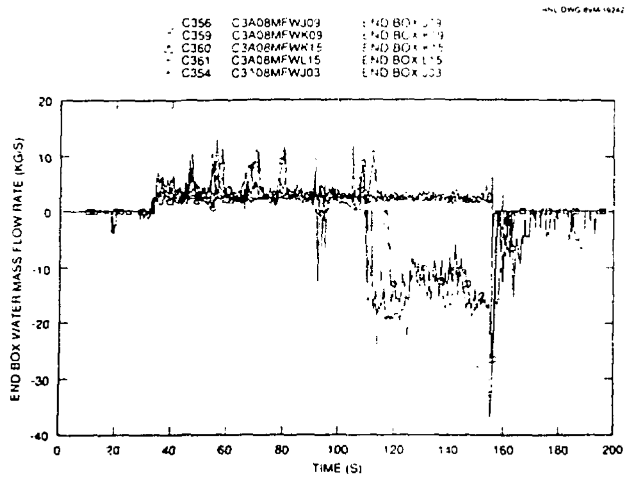

Fig. 15a. Water mass flow rate across tie plate during countercurrent flow test (9).

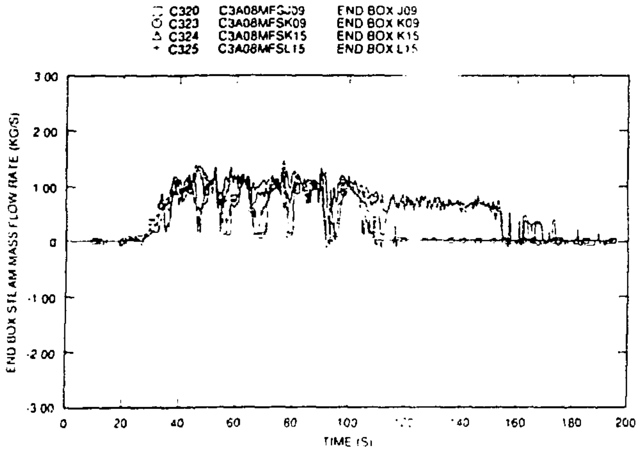

Fig. 15b. Steam mass flow rate across tie plate during countercurrent flow test (9).

REFERENCES

1. L. S. Tong, "Technical Perspective and Objectives of 2D/3D Research Program," presented at the 8th Water Reactor Safety Research Information Meeting, Gaithersburg, Md., 1980.

2. H. Amano et al., ed., *Progress of Nuclear Safety Research, Part 1,* Reactor Safety Research, Japan Atomic Energy Research Institute, 1980, pp.70-71.

3. E. F. Hicken, and K. R. Hoffman, "The German 2D/3D UPTF Program," Presented at the 8th Water Reactor Safety Research Information Meeting, Gaithersburg, Md., 1980.

4. J. E. Smith, and D. G. Thomas, "Apparatus of Measuring Fluid Flow," U.S. Patent No. 4,481,830, 1984.

5. MPR Associates, *Upper Plenum Test Facility Tie Plate Drag Body Measurement System Functional Specification, Revision 2,* 1982.

6. MPR Associates, *Upper Plenum Test Facility Breakthrough Detector Measurement System Functional Specification, Revision 1,* 1983.

7. J. E. Smith, "Summary of Status and Performance of Tie-Plate Drag Body Transducers," presented at the 2D/3D Program Management Review, Washington, D.C., 1982.

8. D. G. Thomas, and S. K. Combs, *Measurement of Two-Phase Flow at the Core/Upper Plenum Interface for a PWR Geometry Under Simulated Reflood Conditions,* NUREG/CR-3138, ORNL/TM-8204, Oak Ridge National Laboratory, 1983.

9. Private communications from Siemens AG UB KWU.

DISCLAIMER